US009314306B2

(12) **United States Patent**
Yu

(10) **Patent No.: US 9,314,306 B2**
(45) **Date of Patent: Apr. 19, 2016**

(54) **SYSTEMS AND METHODS FOR MANIPULATING AN ELONGATE MEMBER**

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(73) Assignee: **HANSEN MEDICAL, INC.**, Mountain View, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 576 days.

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(22) Filed: **Jun. 30, 2011**

(65) **Prior Publication Data**

US 2012/0071821 A1 Mar. 22, 2012

Related U.S. Application Data

(60) Provisional application No. 61/384,220, filed on Sep. 17, 2010, provisional application No. 61/482,598, filed on May 4, 2011.

(51) **Int. Cl.**

A61B 19/00 (2006.01)
A61B 6/12 (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ***A61B 19/2203*** (2013.01); ***A61B 6/12*** (2013.01); ***A61B 6/4423*** (2013.01); ***A61B 8/12*** (2013.01); ***A61B 8/4218*** (2013.01); ***G06T 19/00*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC A61B 19/22–19/2296
USPC 606/1
See application file for complete search history.

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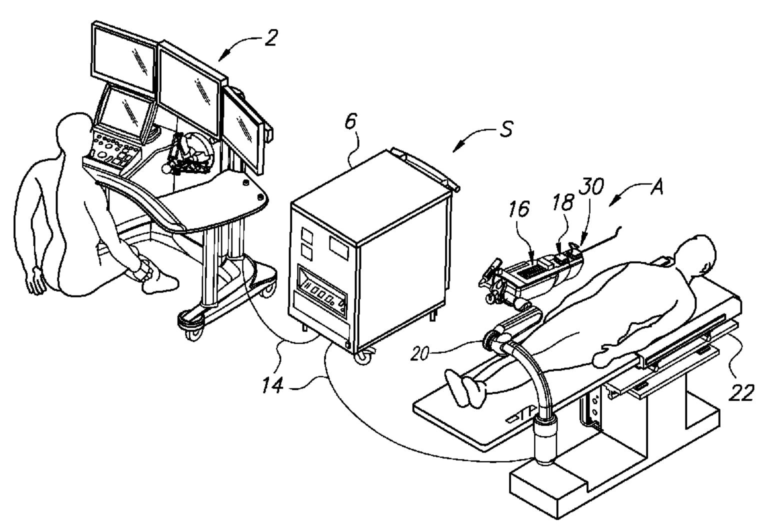
Primary Examiner — Lynsey Crandall

(74) *Attorney, Agent, or Firm* — Scott M. Smith; Dorsey & Whitney LLP

(57) **ABSTRACT**

System and methods for manipulating and positioning elongated flexible members are described herein. In on variation, an elongate member manipulator includes an elongate member holder having first and second rotary members configured to hold an elongate member, wherein the rotary members are actuated in opposite rotational directions to generate a corresponding linear motion of the elongate member held by the rotary members along a longitudinal axis of the elongate member, and wherein the rotary members are actuated in opposite linear directions to generate a corresponding rotational motion of the elongate member held by the rotary members about the longitudinal axis of the elongate member.

13 Claims, 194 Drawing Sheets



(51) **Int. Cl.**

A61B 8/12	(2006.01)
A61B 8/00	(2006.01)
G06T 19/00	(2011.01)
A61B 6/00	(2006.01)
A61B 8/08	(2006.01)

(52) **U.S. Cl.**

CPC *A61B 6/487* (2013.01); *A61B 8/0841* (2013.01); *A61B 2019/2211* (2013.01); *A61B 2019/2219* (2013.01); *A61B 2019/2223* (2013.01); *A61B 2019/2246* (2013.01); *G06T 2210/41* (2013.01)

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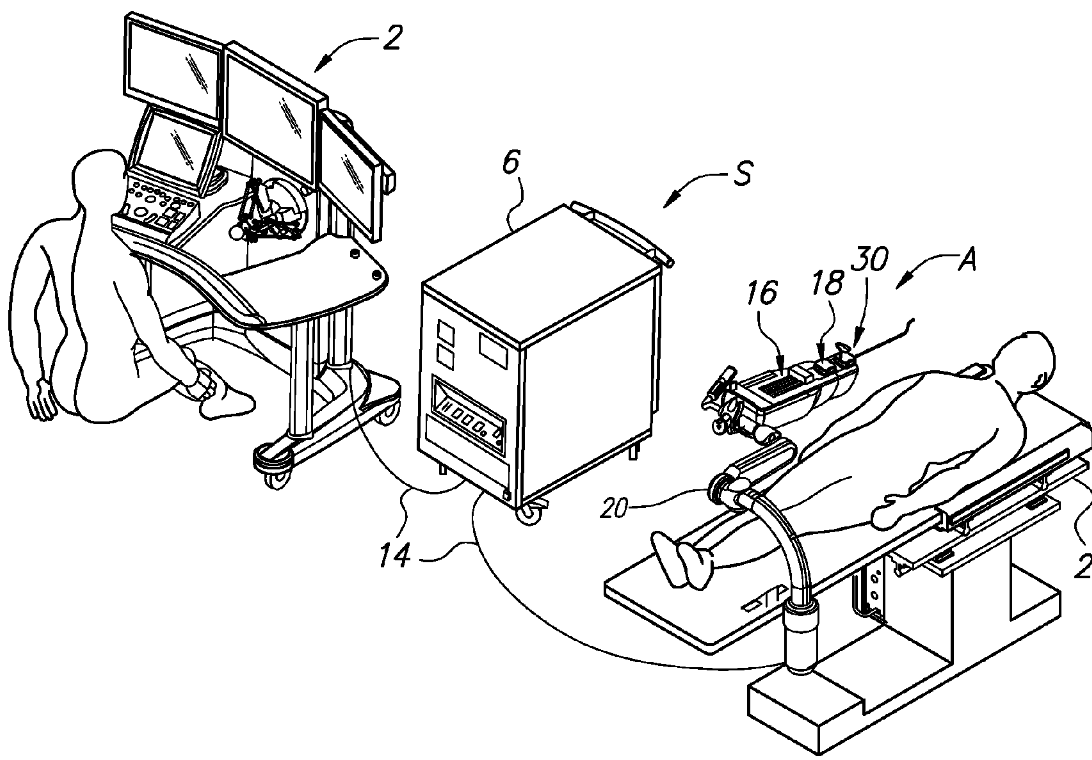


FIG. 1

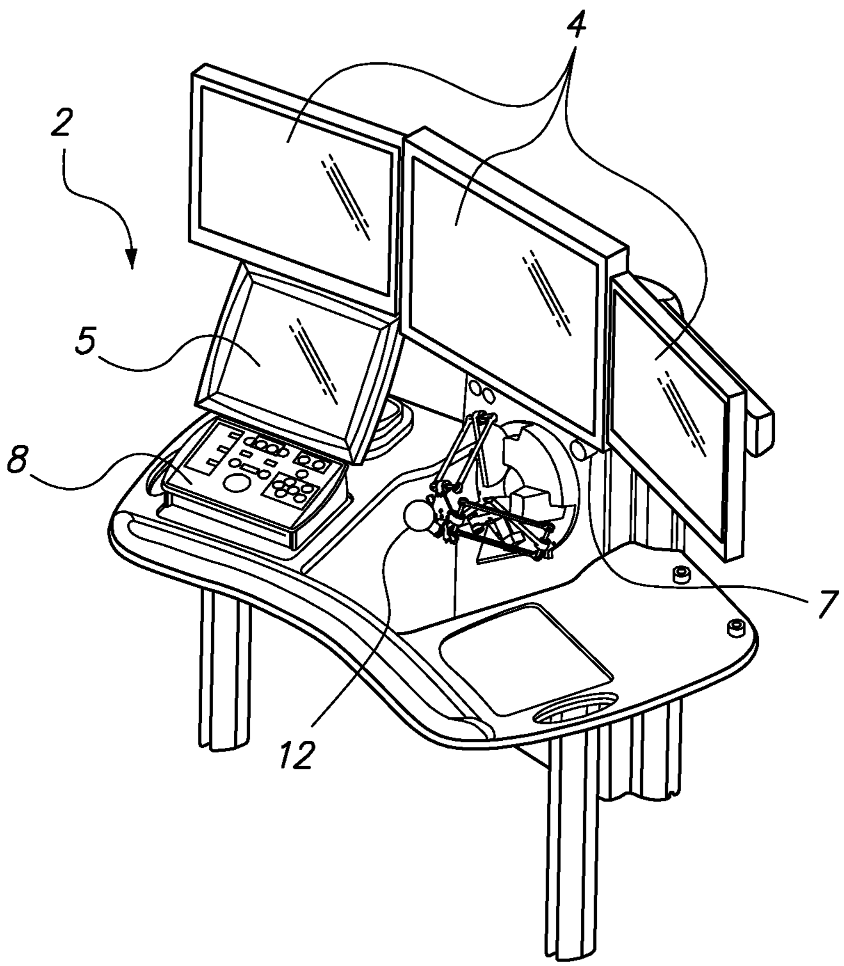


FIG. 2

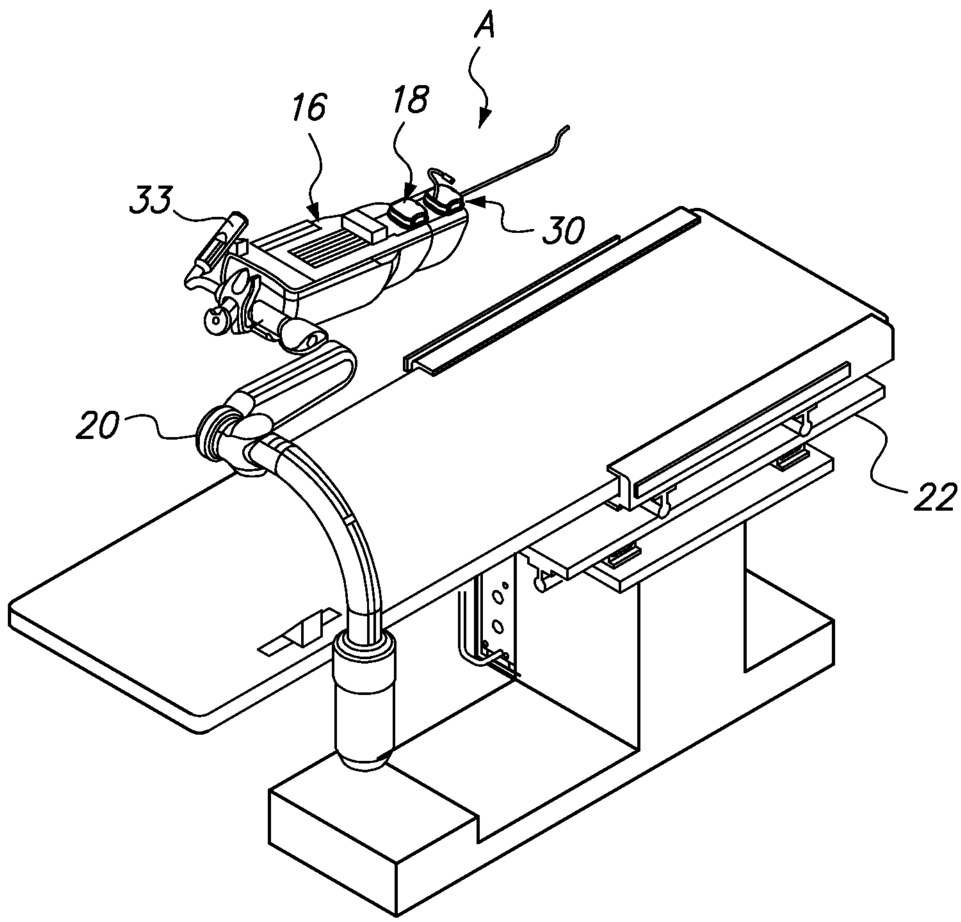


FIG. 3A

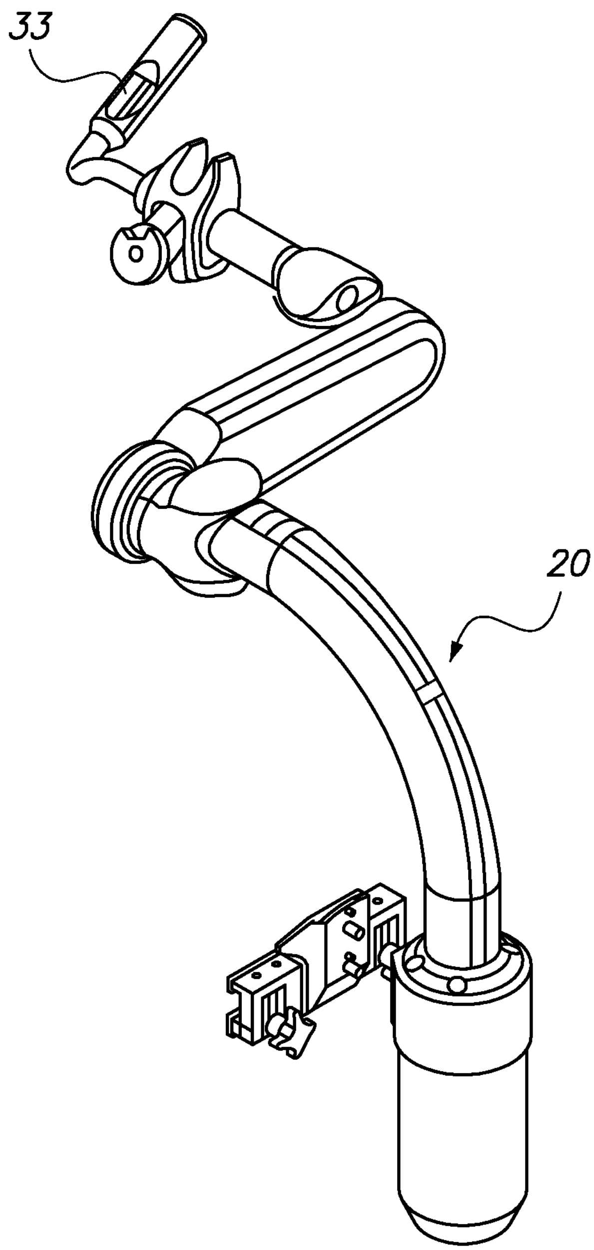


FIG. 3B

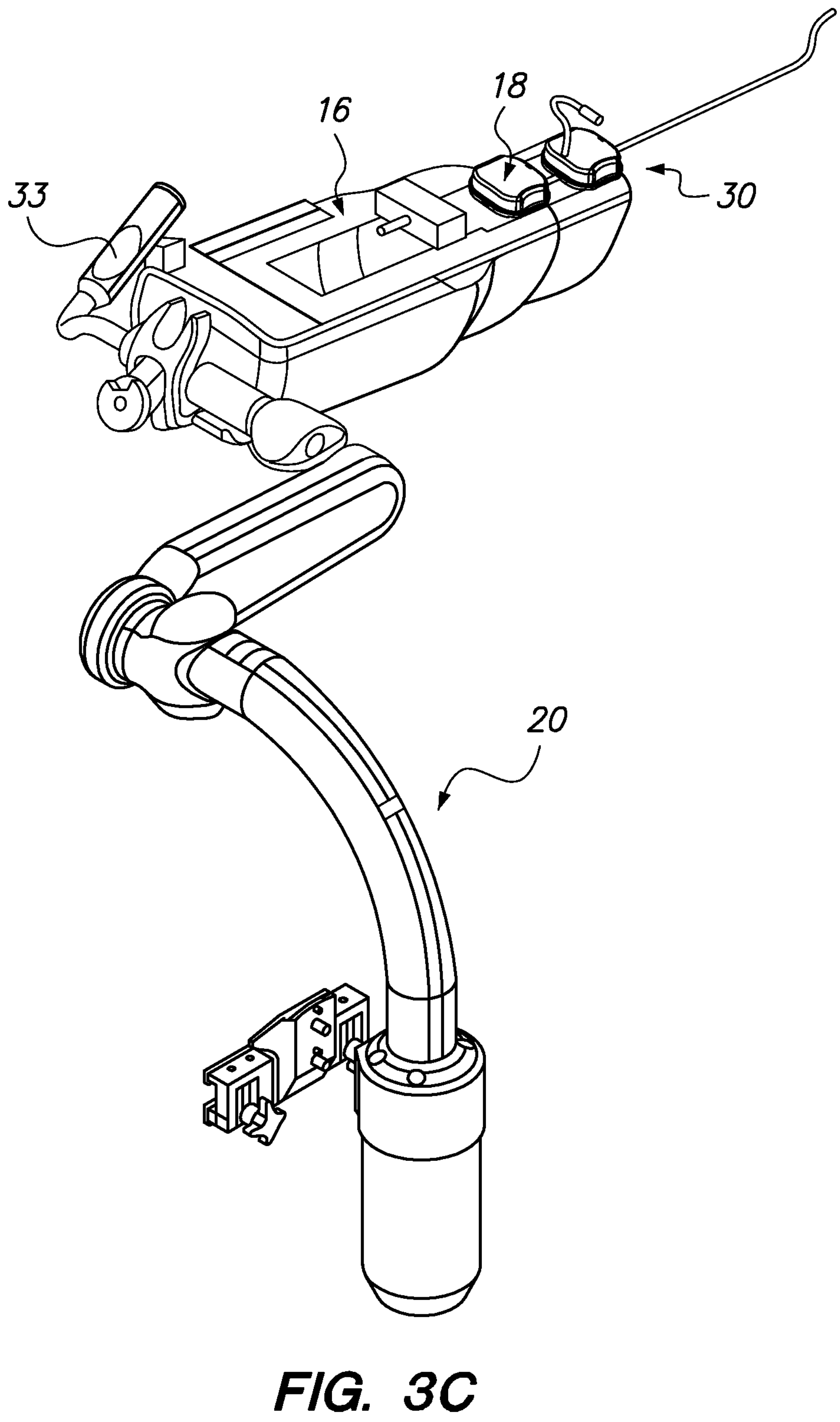


FIG. 3C

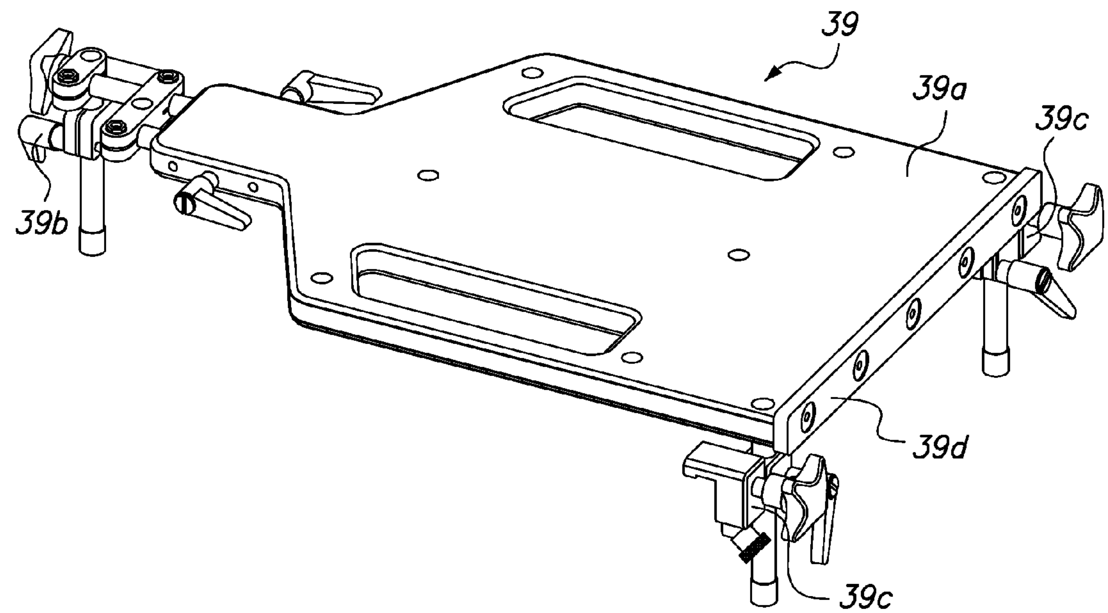


FIG. 3D

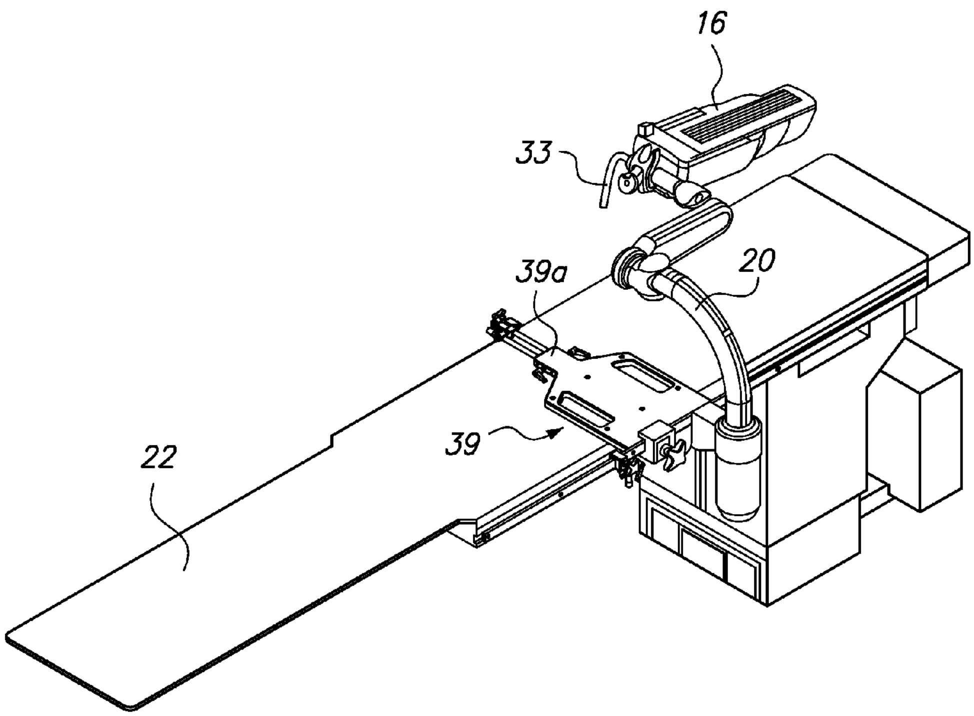
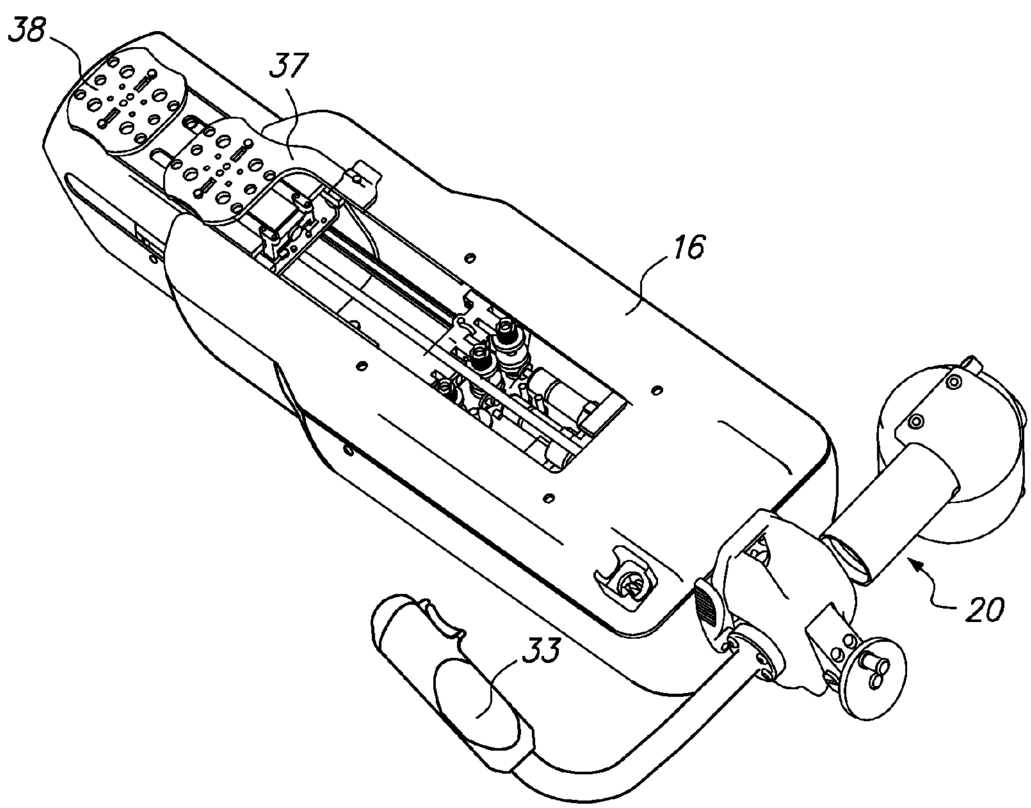


FIG. 3E



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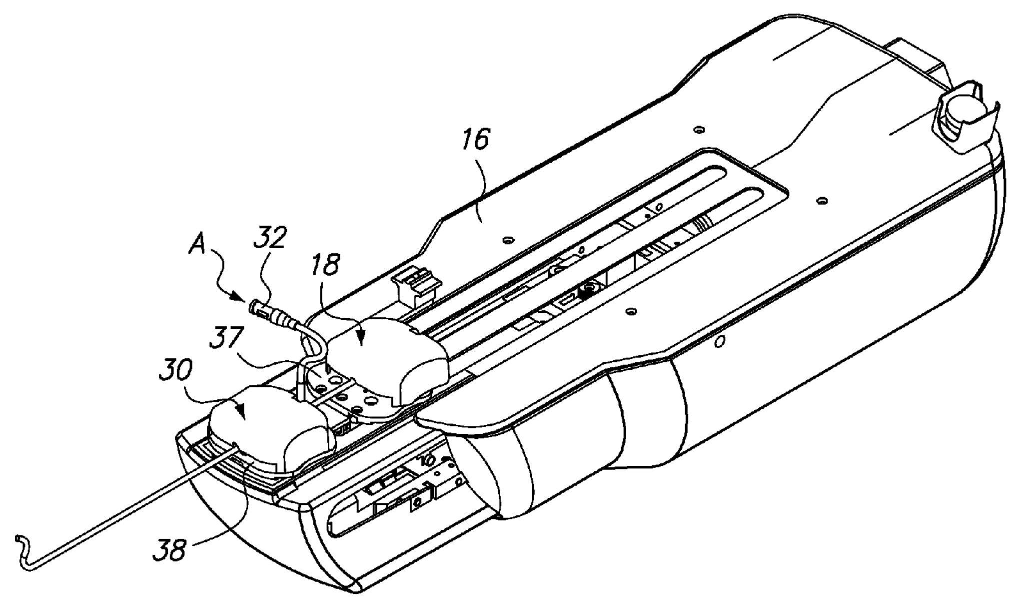


FIG. 5A

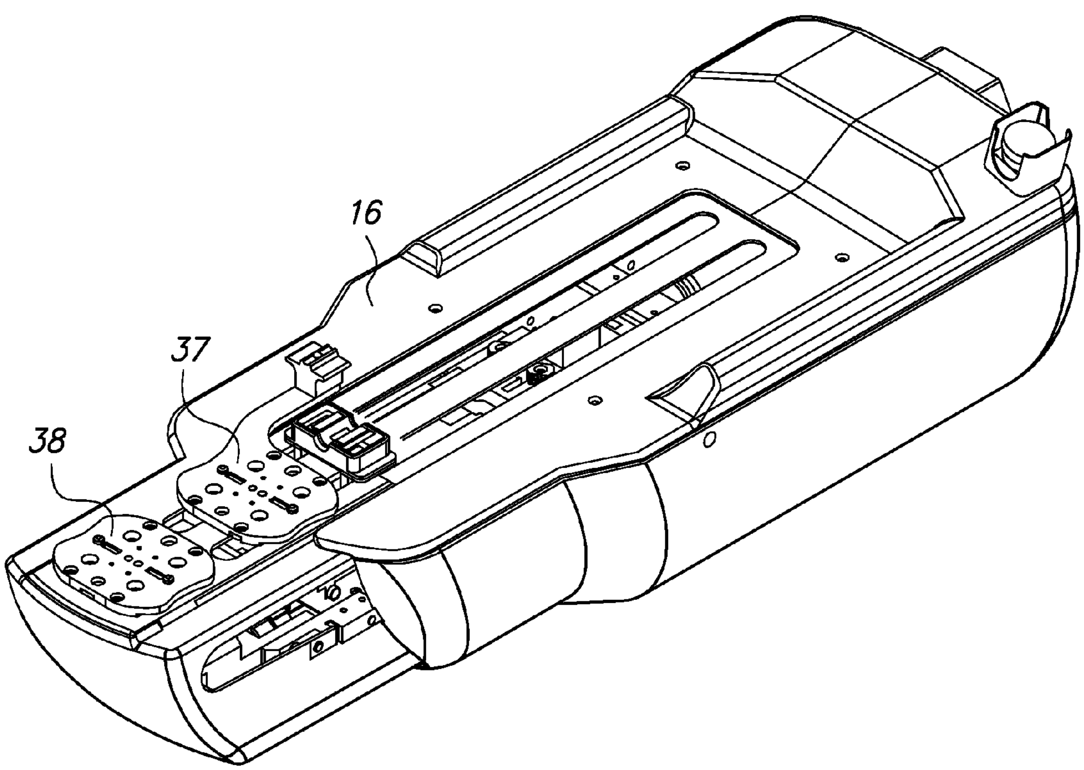


FIG. 5B

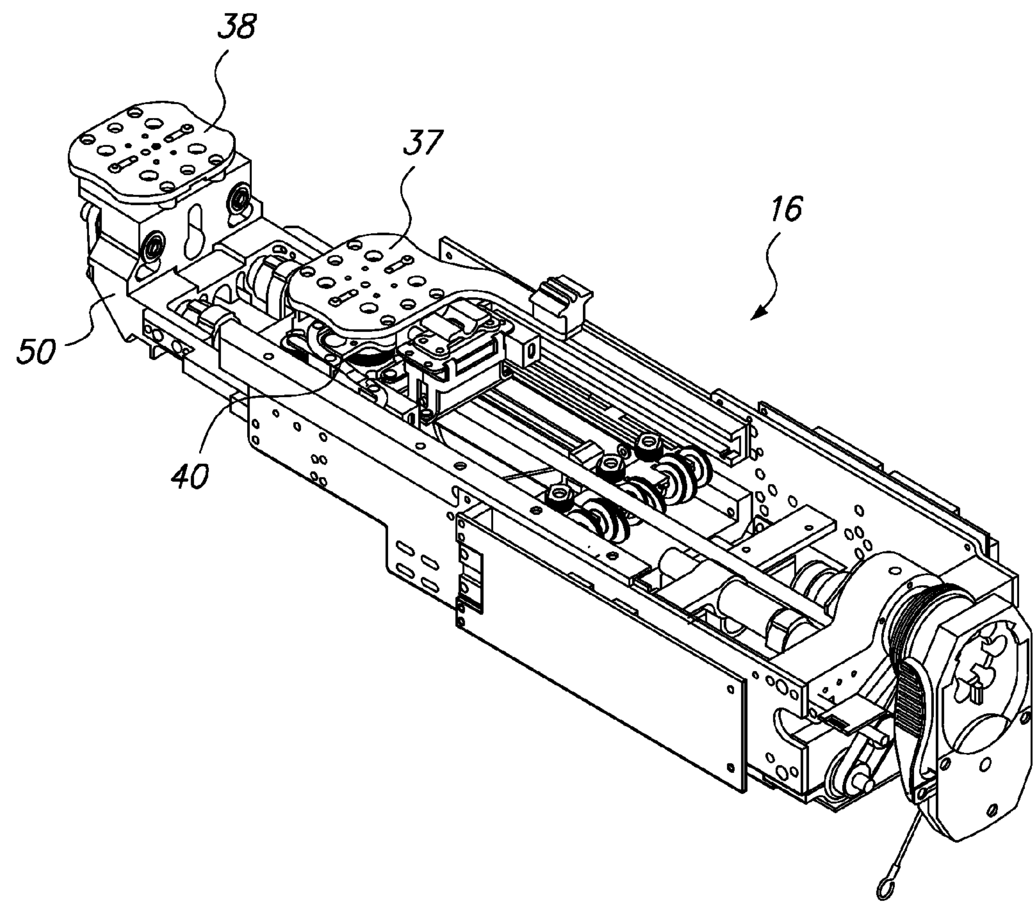


FIG. 5C

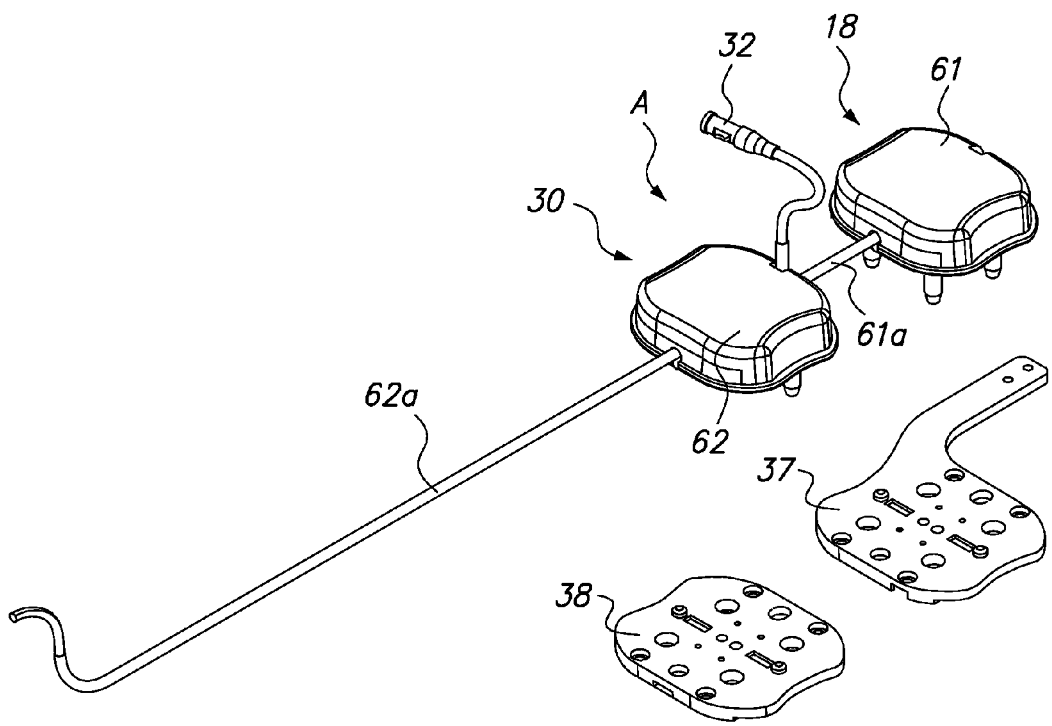
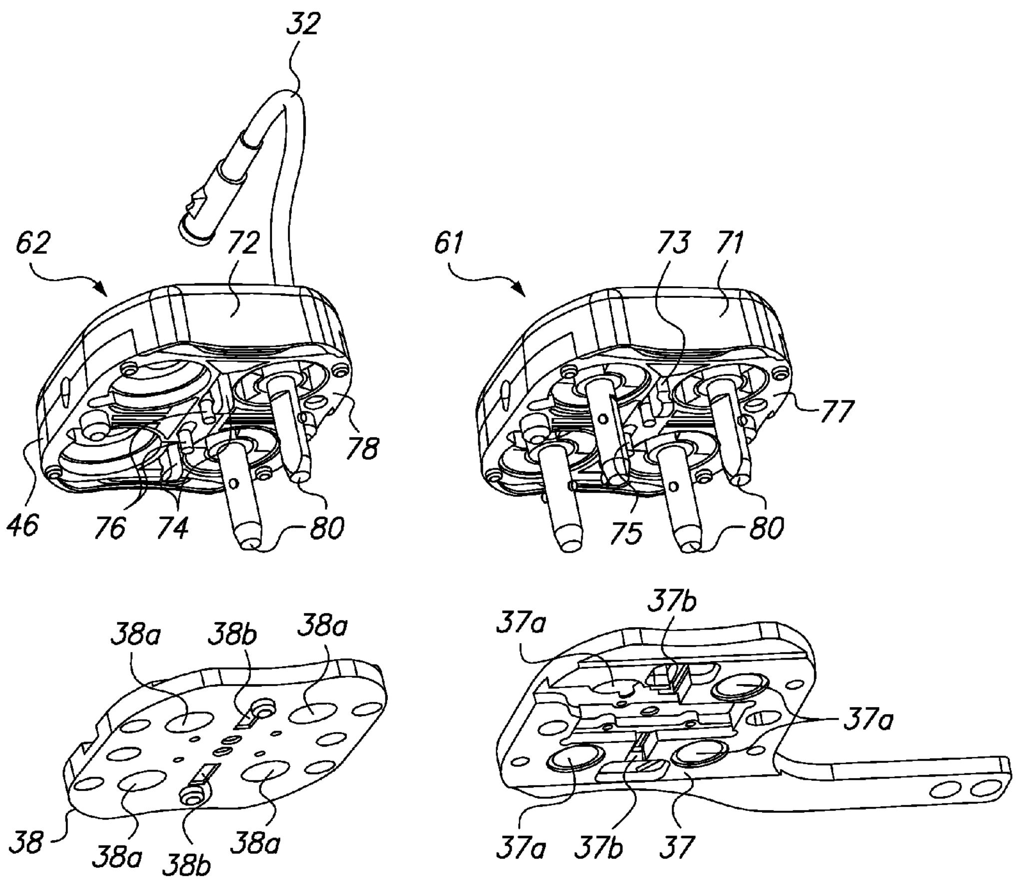


FIG. 6A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38b
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37a
37b
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FIG. 6B

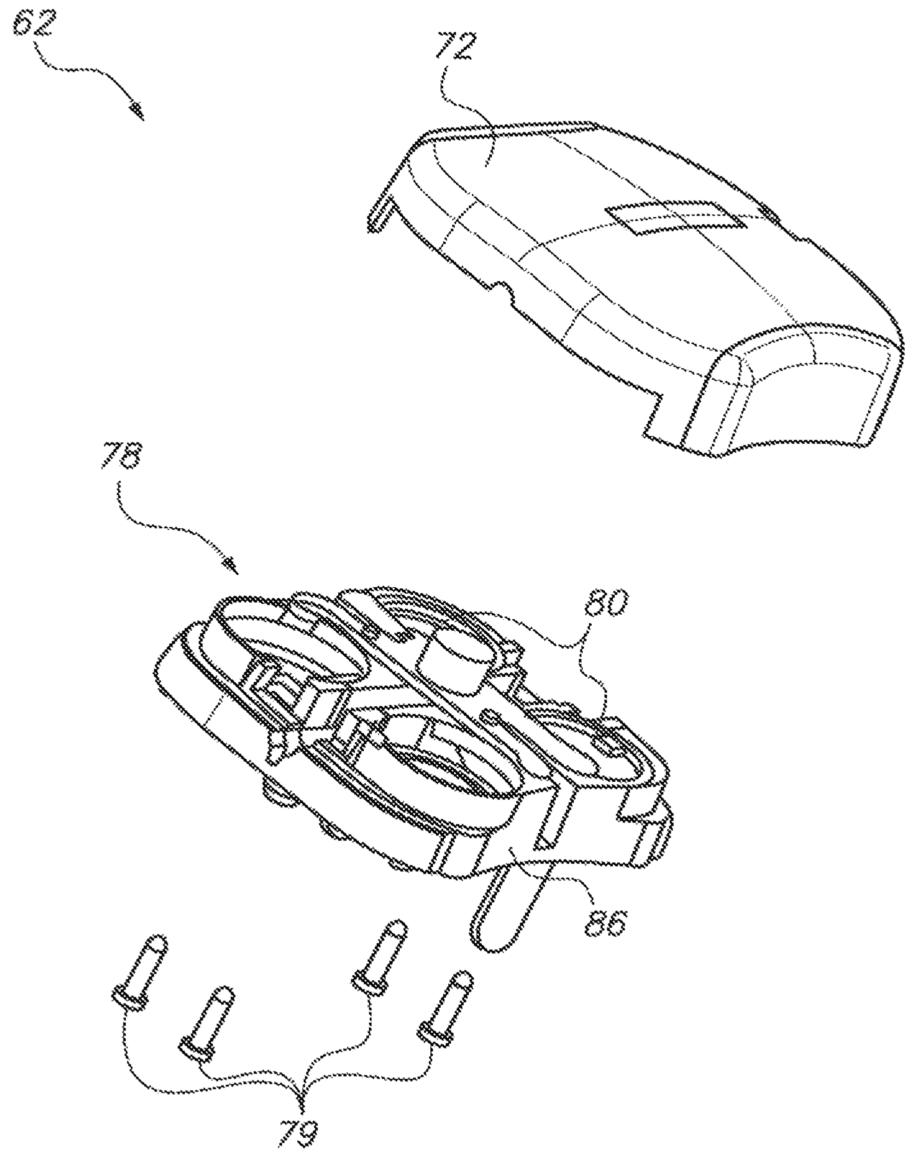


FIG. 7

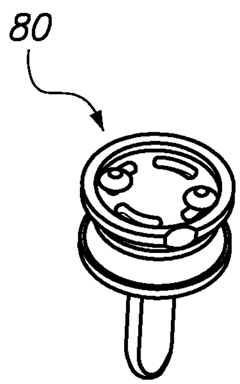


FIG. 7A

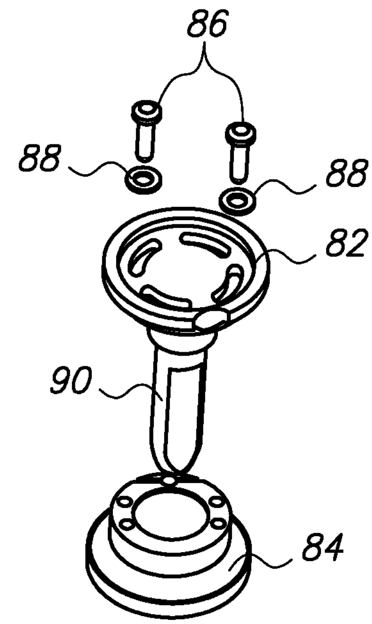
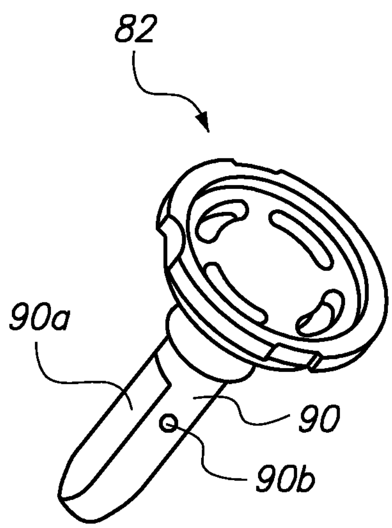


FIG. 7B



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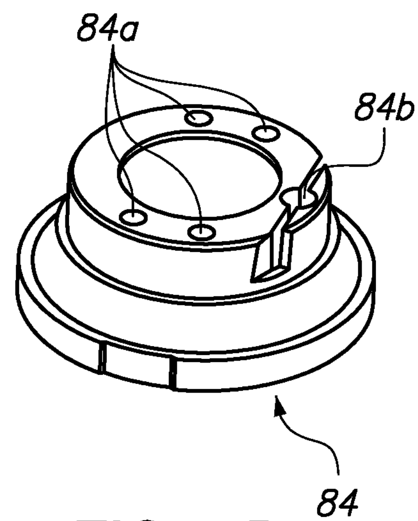


FIG. 7D

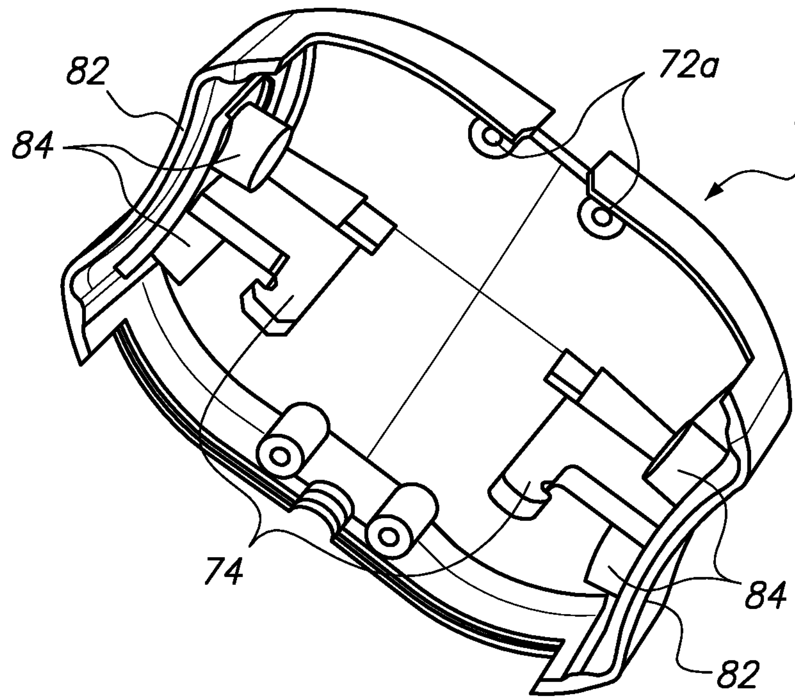


FIG. 7E

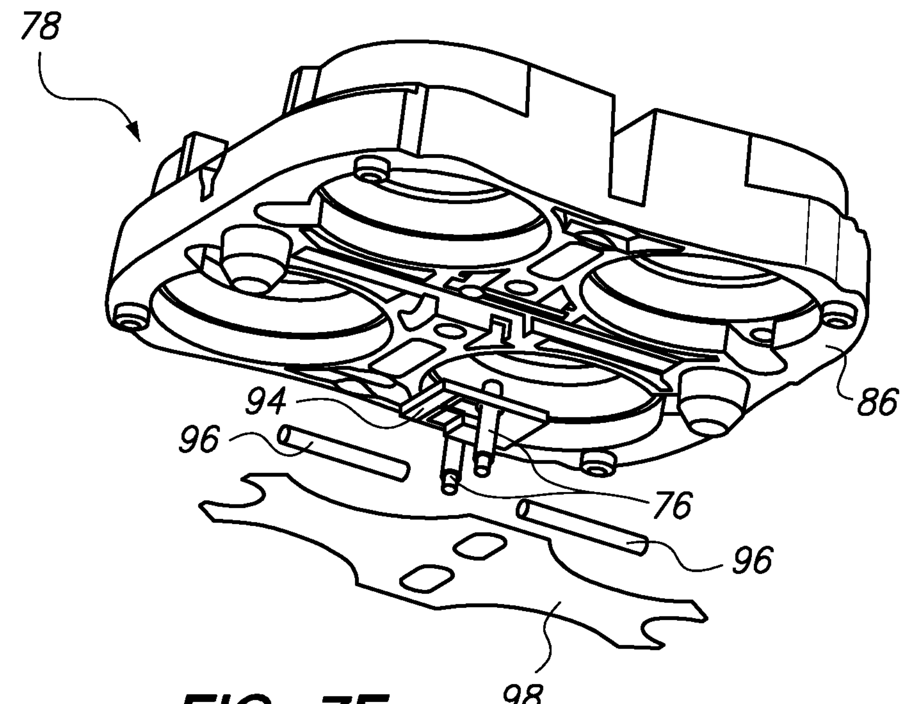


FIG. 7F

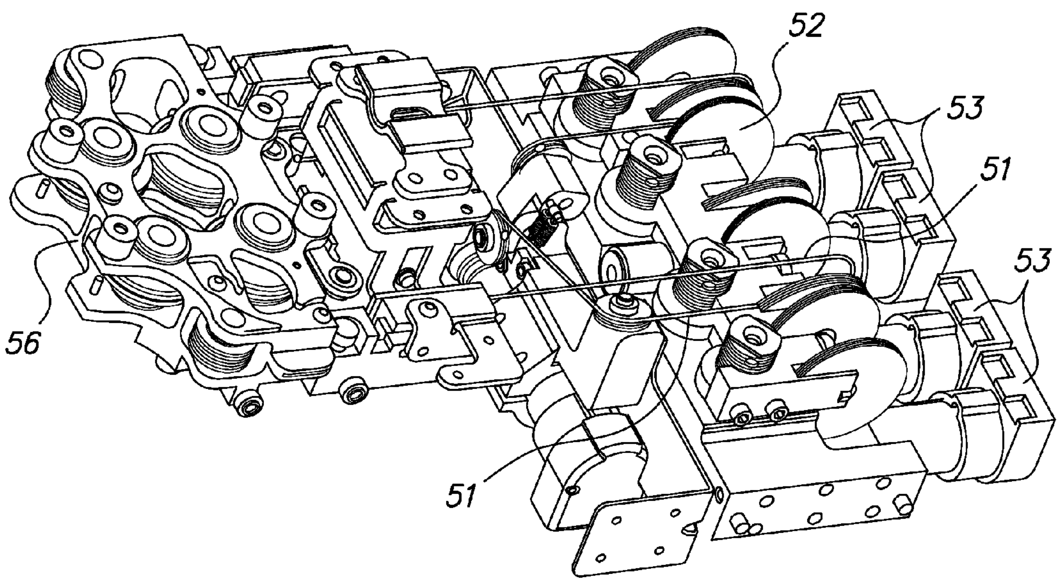
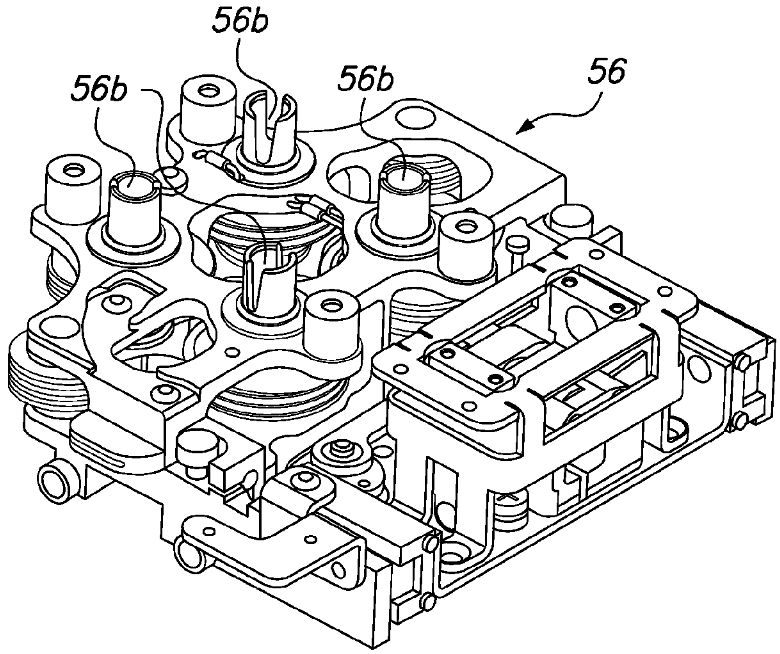


FIG. 8A



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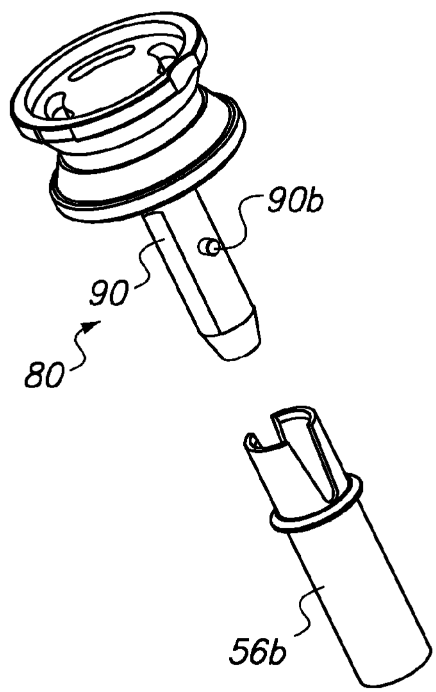


FIG. 9A

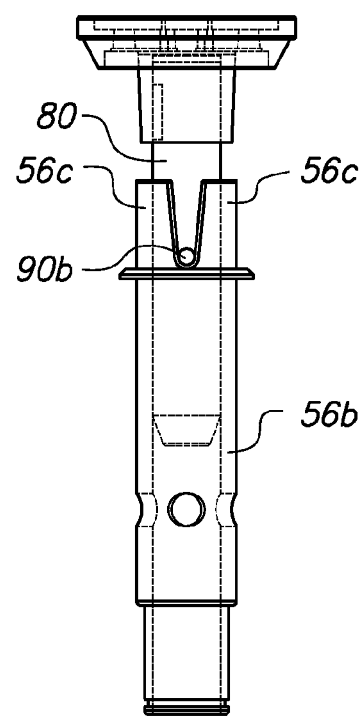
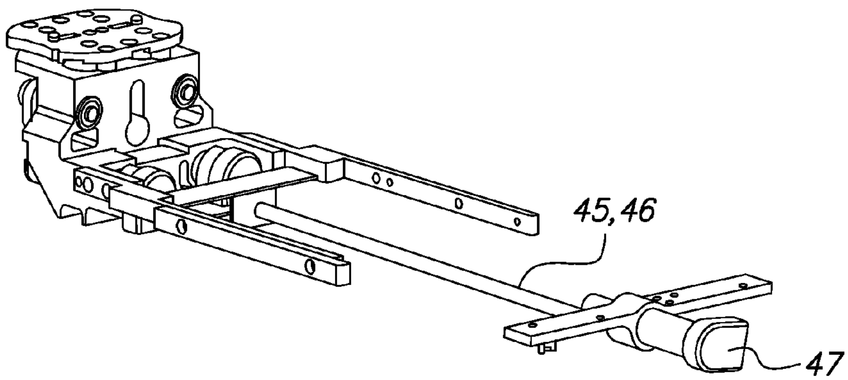


FIG. 9B



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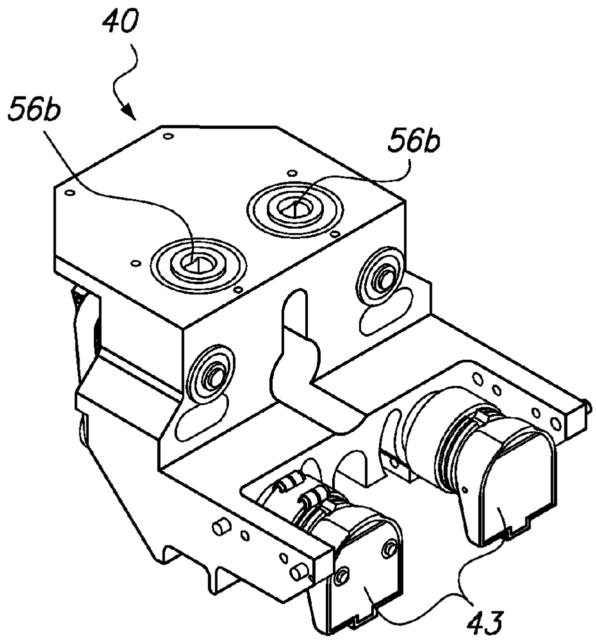
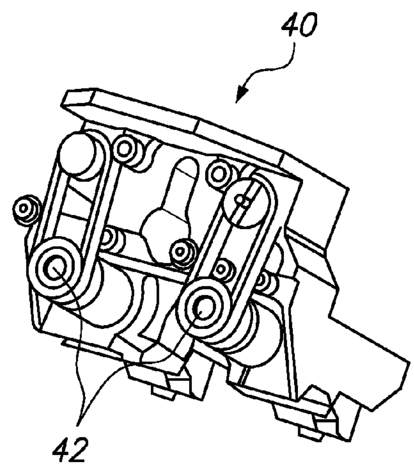


FIG. 10A



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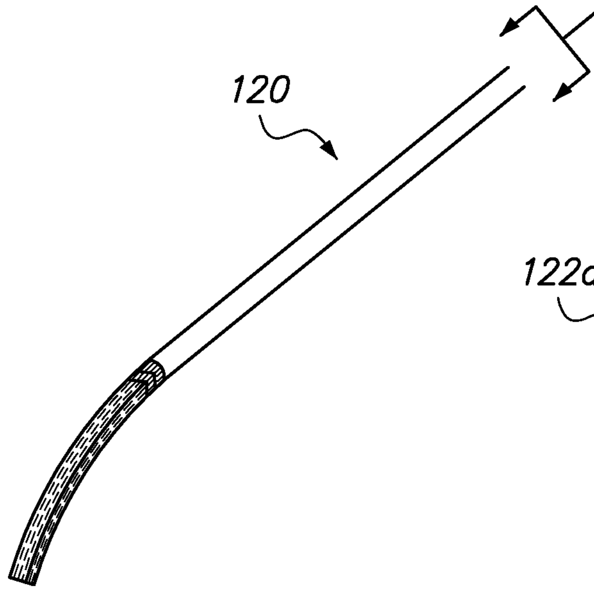


FIG. 11A

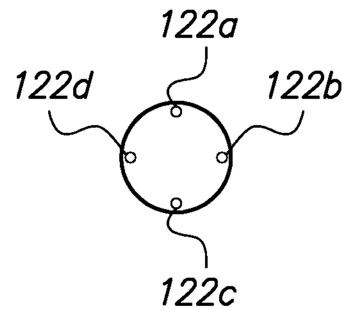


FIG. 11B

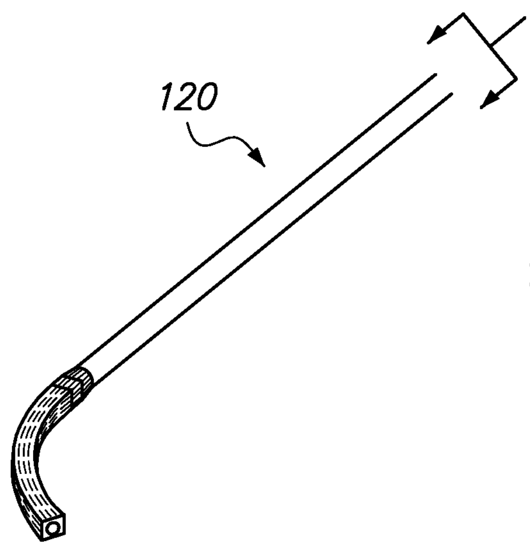


FIG. 11C

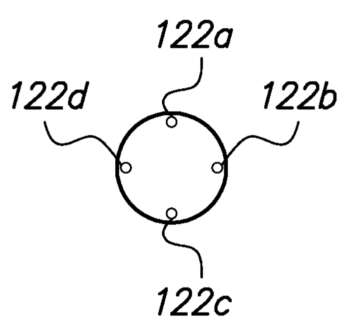


FIG. 11D

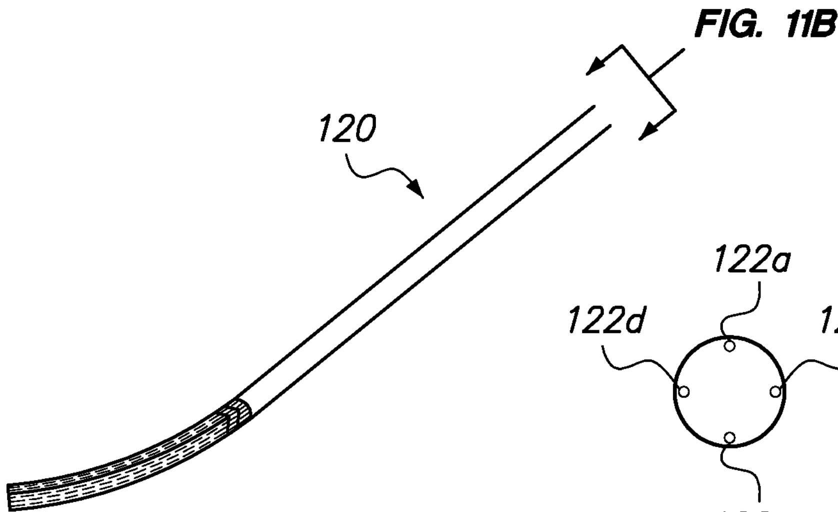


FIG. 11E

FIG. 11F

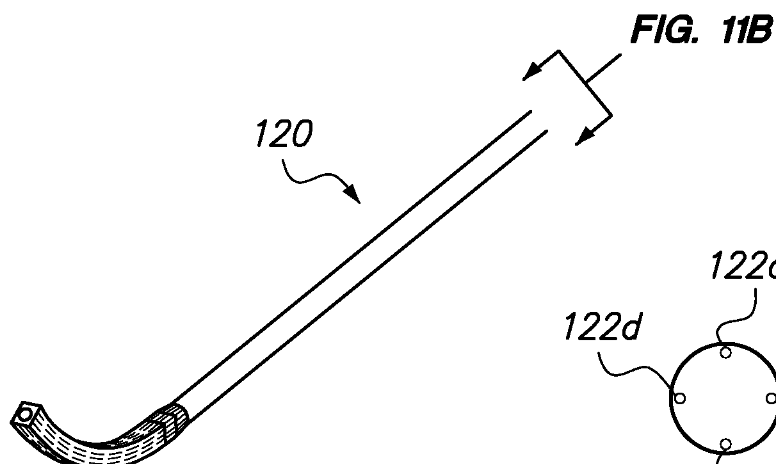


FIG. 11G

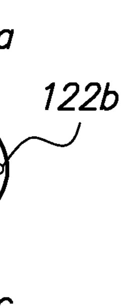


FIG. 11H

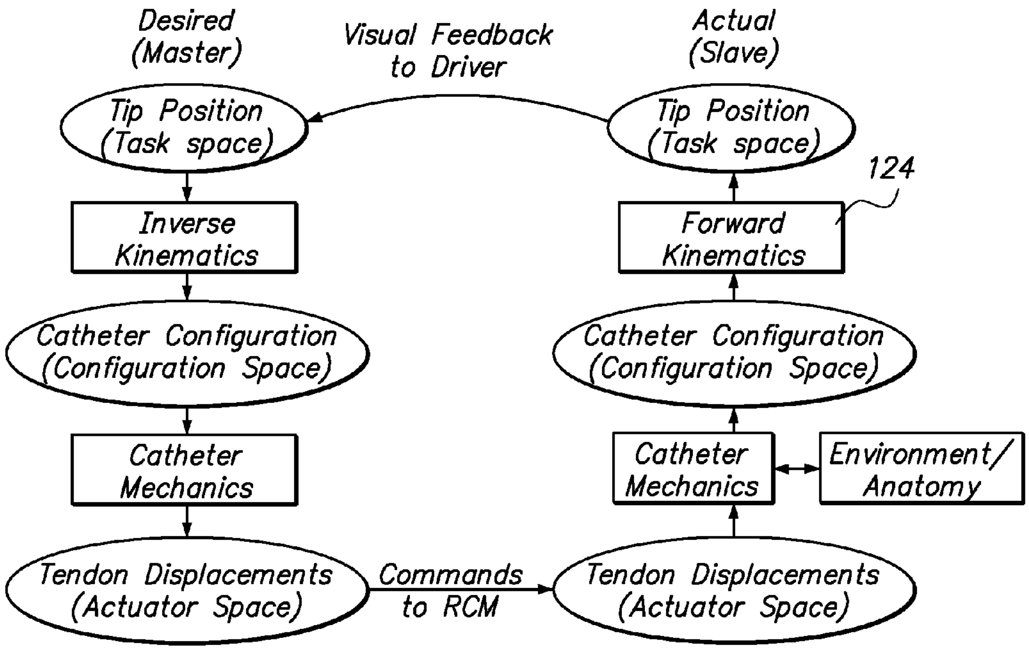

Desired
(Master)
Visual Feedback
to Driver
Actual
(Slave)
Tip Position
(Task space)
Tip Position
(Task space)
124
Inverse
Kinematics
Forward
Kinematics
Catheter Configuration
(Configuration Space)
Catheter Configuration
(Configuration Space)
Catheter
Mechanics
Catheter
Mechanics
Environment/
Anatomy
Tendon Displacements
(Actuator Space)
Commands
to RCM
Tendon Displacements
(Actuator Space)

FIG. 12

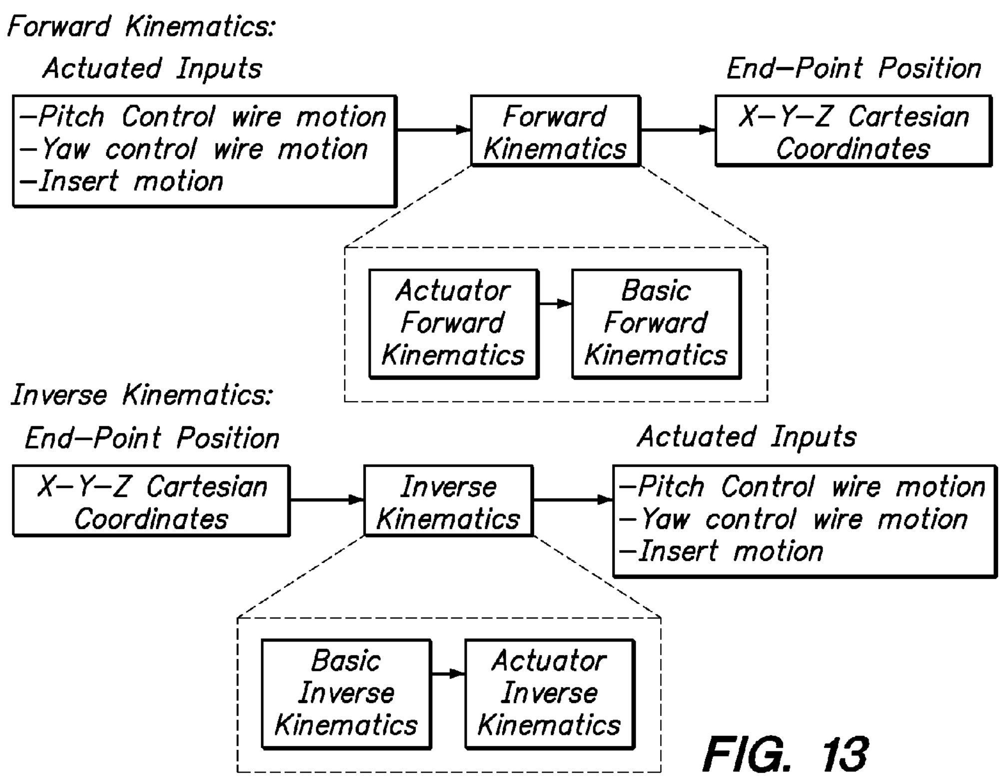
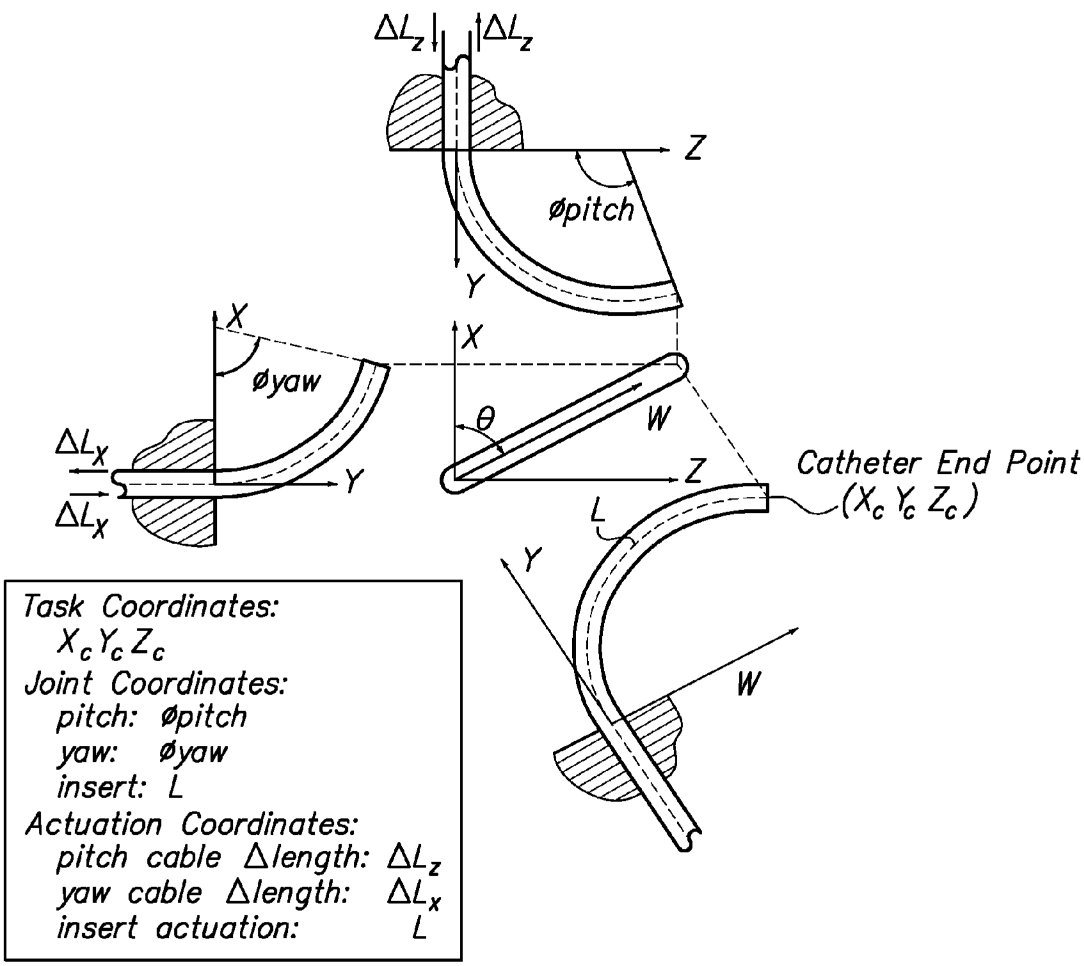

Forward Kinematics:
Actuated Inputs
End–Point Position
–Pitch Control wire motion
–Yaw control wire motion
–Insert motion
Forward
Kinematics
X–Y–Z Cartesian
Coordinates
Actuator
Forward
Kinematics
Basic
Forward
Kinematics
Inverse Kinematics:
End–Point Position
Actuated Inputs
X–Y–Z Cartesian
Coordinates
Inverse
Kinematics
–Pitch Control wire motion
–Yaw control wire motion
–Insert motion
Basic
Inverse
Kinematics
Actuator
Inverse
Kinematics

FIG. 13


ΔLz
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X
Øyaw
X
θ
W
ΔLx
ΔLx
Y
Z
Catheter End Point
(Xc Yc Zc)
L
Y
W
Task Coordinates:
Xc Yc Zc
Joint Coordinates:
pitch: Øpitch
yaw: Øyaw
insert: L
Actuation Coordinates:
pitch cable Δlength: ΔLz
yaw cable Δlength: ΔLx
insert actuation: L

FIG. 14

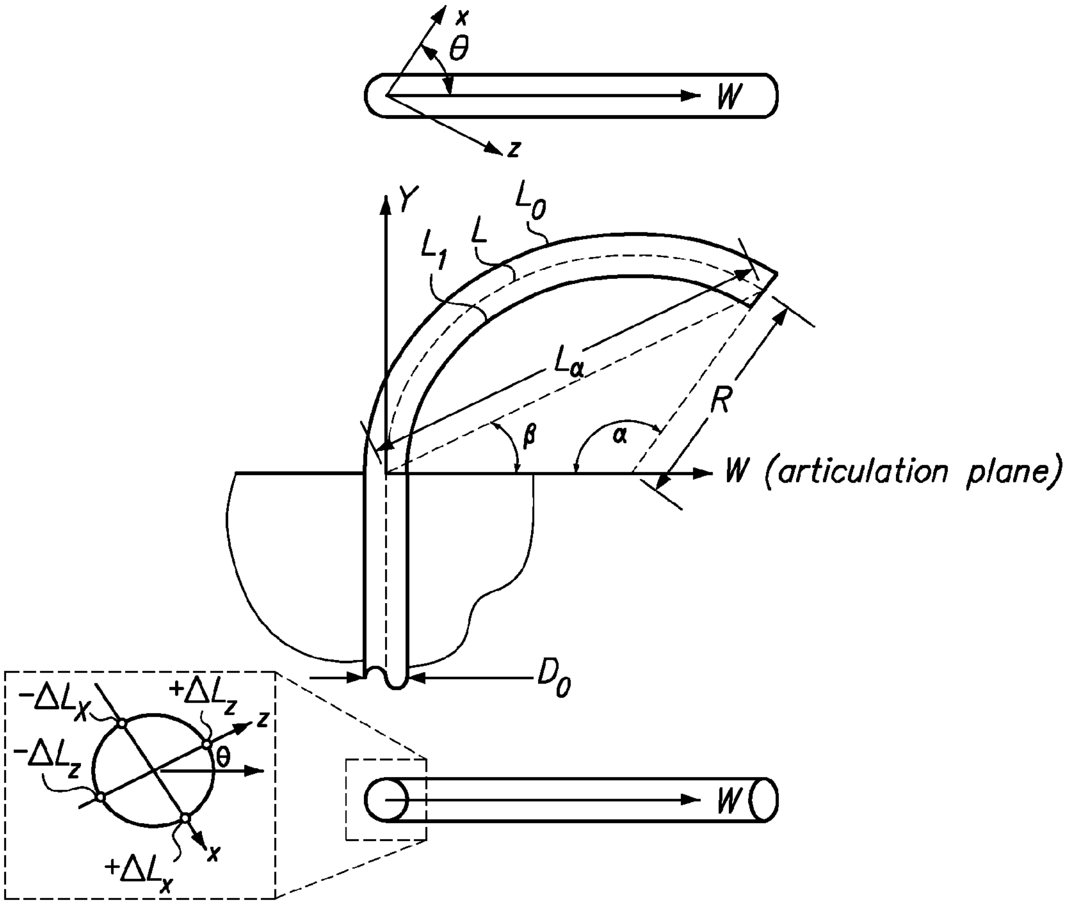

x
θ
W
z
Y
L_0
L
L_1
L_α
R
β
α
W (articulation plane)
D_0
$-\Delta L_x$
$+\Delta L_z$
z
$-\Delta L_z$
θ
x
$+\Delta L_x$
W

FIG. 15

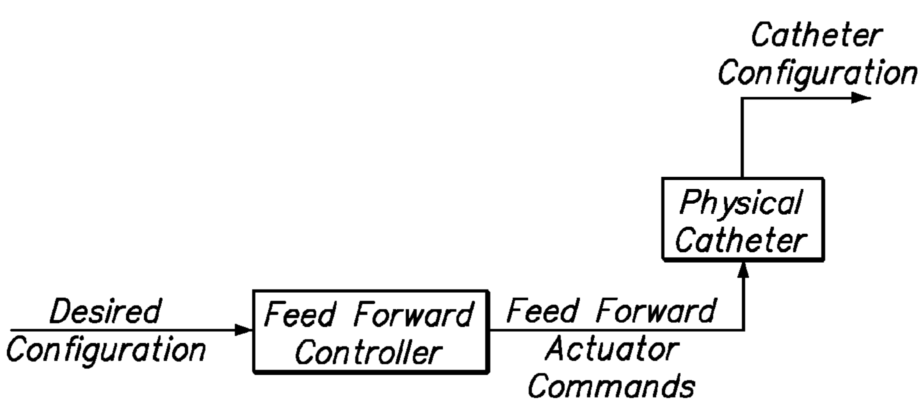

Catheter Configuration
Physical Catheter
Desired Configuration
Feed Forward Controller
Feed Forward Actuator Commands

FIG. 16

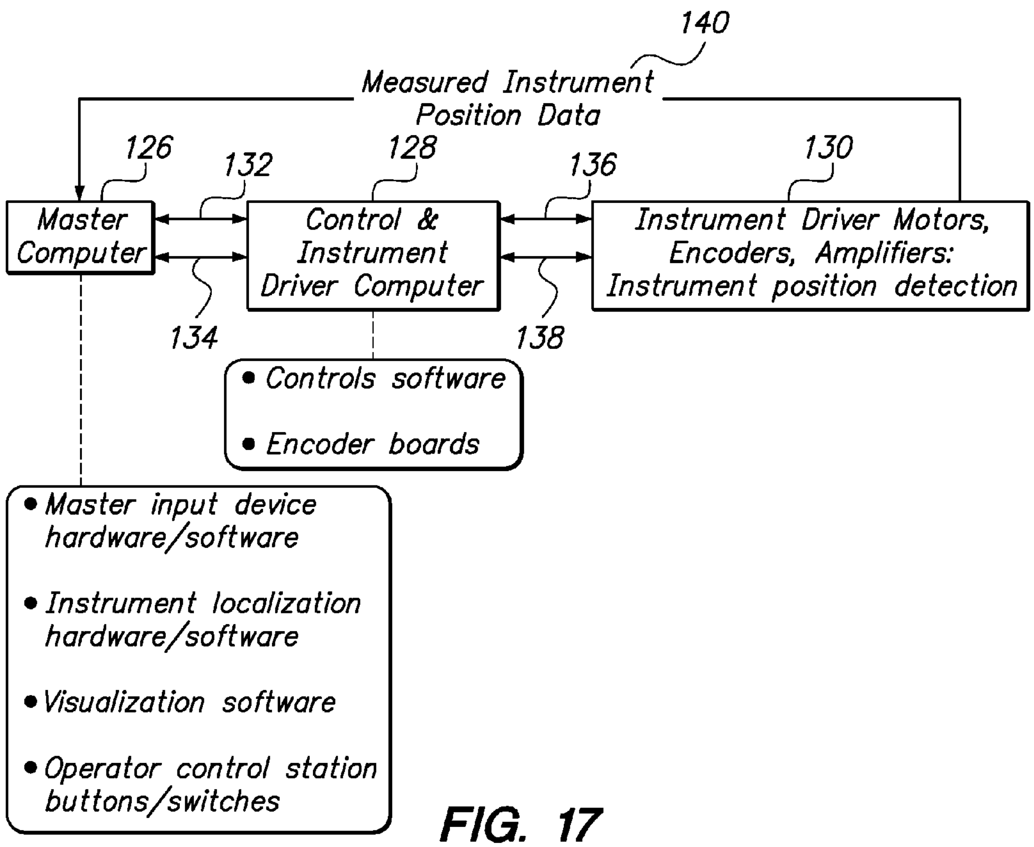

140
Measured Instrument Position Data
126
132
128
136
130
Master Computer
Control & Instrument Driver Computer
Instrument Driver Motors, Encoders, Amplifiers: Instrument position detection
134
138
• Controls software
• Encoder boards
• Master input device hardware/software
• Instrument localization hardware/software
• Visualization software
• Operator control station buttons/switches

FIG. 17

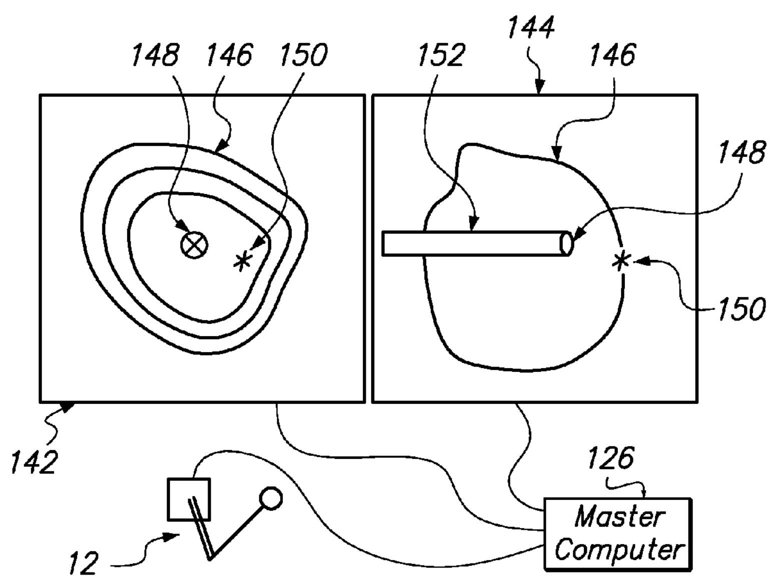
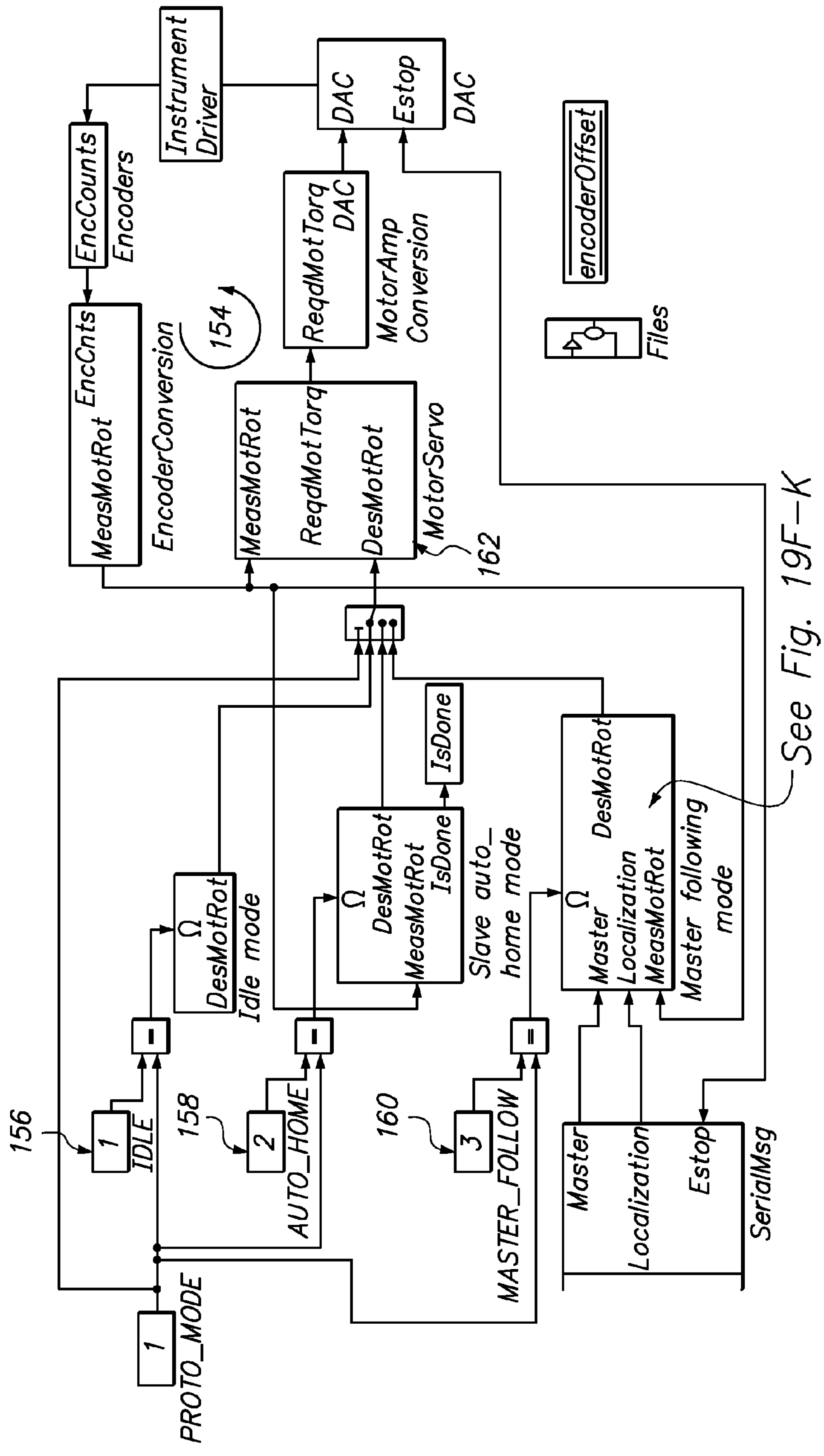
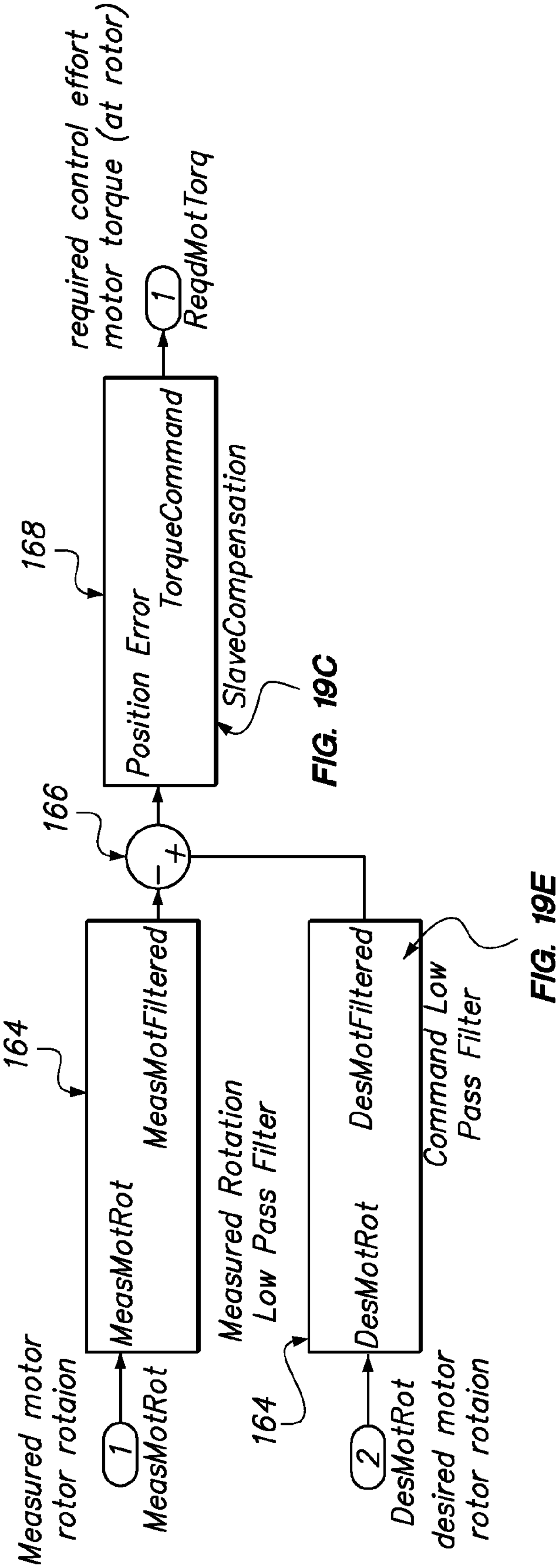

148
146
150
152
144
146
148
150
142
126
Master Computer
12

FIG. 18



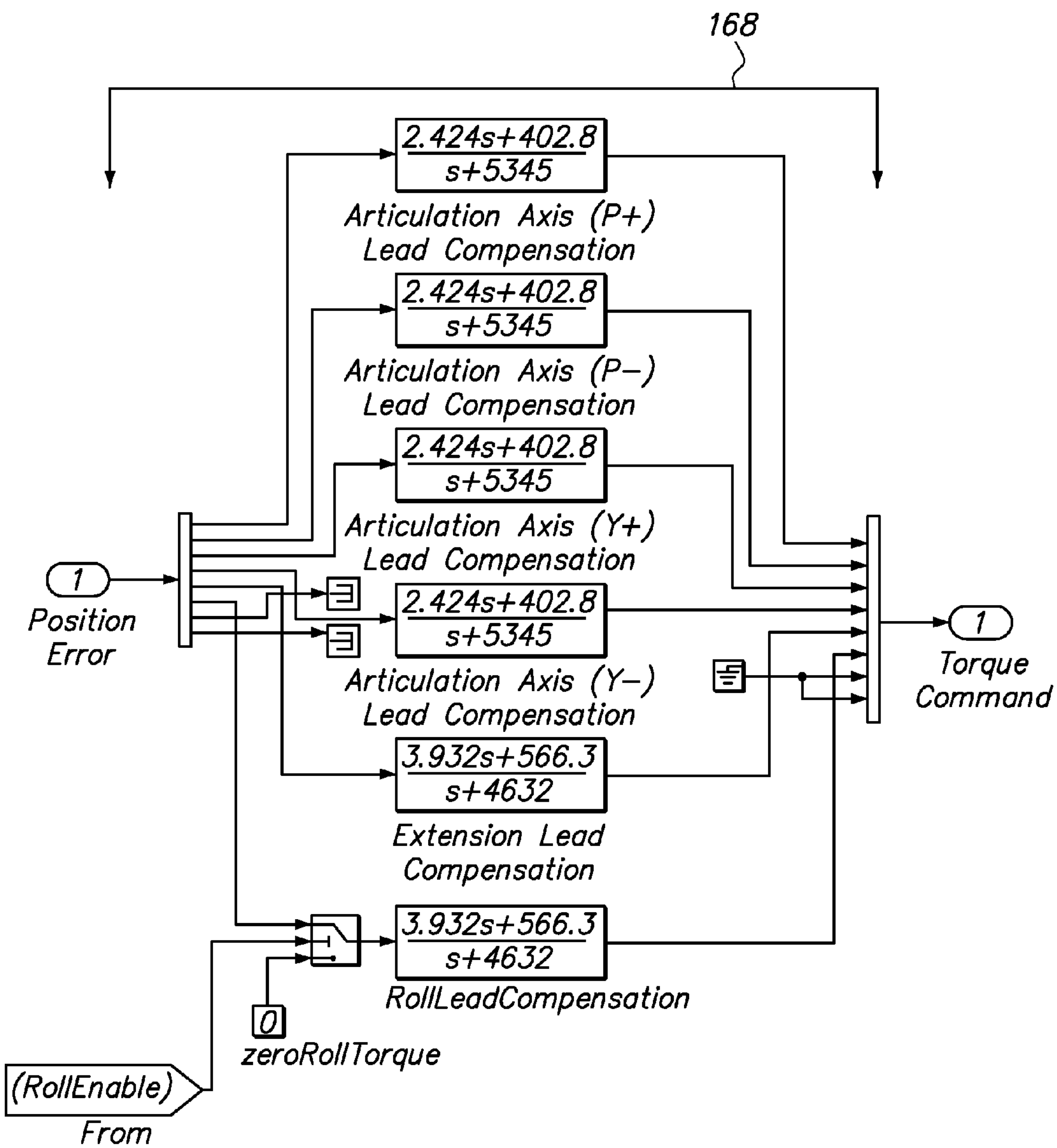
Instrument Driver
EncCounts
Encoders
DAC
Estop
DAC
EncCnts
MeasMotRot
EncoderConversion
154
ReqdMotTorq
DAC
MotorAmp Conversion
encoderOffset
Files
MeasMotRot
ReqdMotTorq
DesMotRot
MotorServo
162
See Fig. 19F–K
IsDone
Ω
DesMotRot
Idle mode
Ω
DesMotRot
MeasMotRot
IsDone
Slave auto_ home mode
Ω
Master
Localization
MeasMotRot
DesMotRot
Master following mode
156
1
IDLE
158
2
AUTO_HOME
160
3
MASTER_FOLLOW
1
PROTO_MODE
Master
Localization
Estop
SerialMsg

FIG. 19



Measured motor rotor rotaion
1
MeasMotRot
MeasMotRot
MeasMotFiltered
164
Measured Rotation Low Pass Filter
164
2
DesMotRot
desired motor rotor rotaion
DesMotRot
DesMotFiltered
Command Low Pass Filter
FIG. 19E
166
−
+
168
Position Error
TorqueCommand
SlaveCompensation
FIG. 19C
1
ReqdMotTorq
required control effort motor torque (at rotor)

FIG. 20



168
2.424s+402.8
s+5345
Articulation Axis (P+)
Lead Compensation
2.424s+402.8
s+5345
Articulation Axis (P–)
Lead Compensation
2.424s+402.8
s+5345
Articulation Axis (Y+)
Lead Compensation
1
Position
Error
2.424s+402.8
s+5345
Articulation Axis (Y–)
Lead Compensation
1
Torque
Command
3.932s+566.3
s+4632
Extension Lead
Compensation
3.932s+566.3
s+4632
RollLeadCompensation
0
zeroRollTorque
(RollEnable)
From

FIG. 21

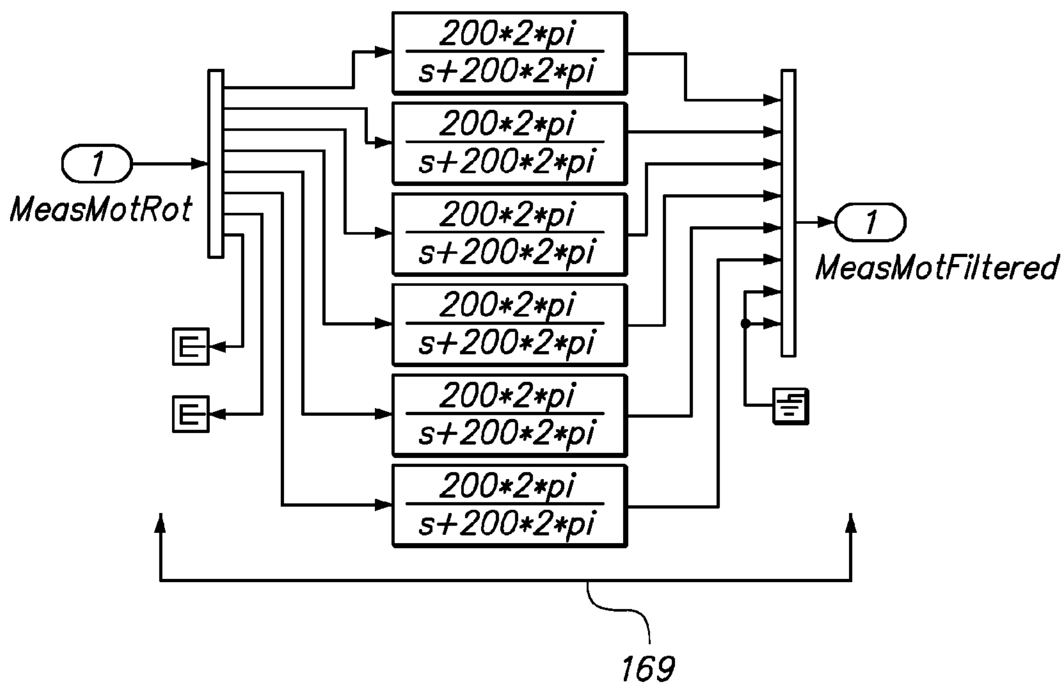

200*2*pi
s+200*2*pi
1
MeasMotRot
1
MeasMotFiltered
169

FIG. 22

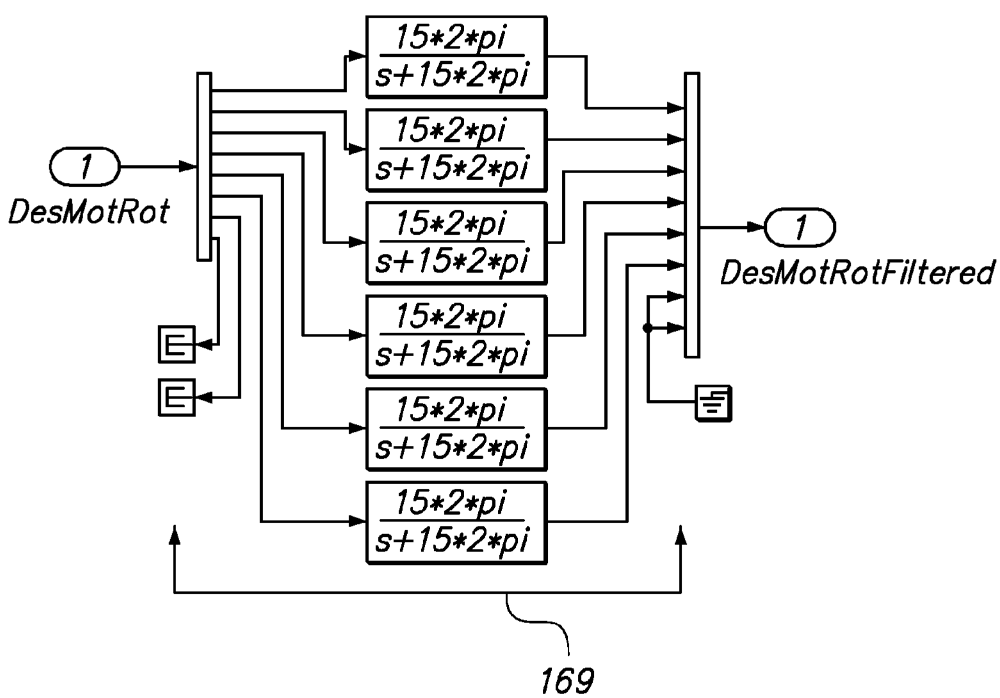

15*2*pi
s+15*2*pi
1
DesMotRot
1
DesMotRotFiltered
169

FIG. 23

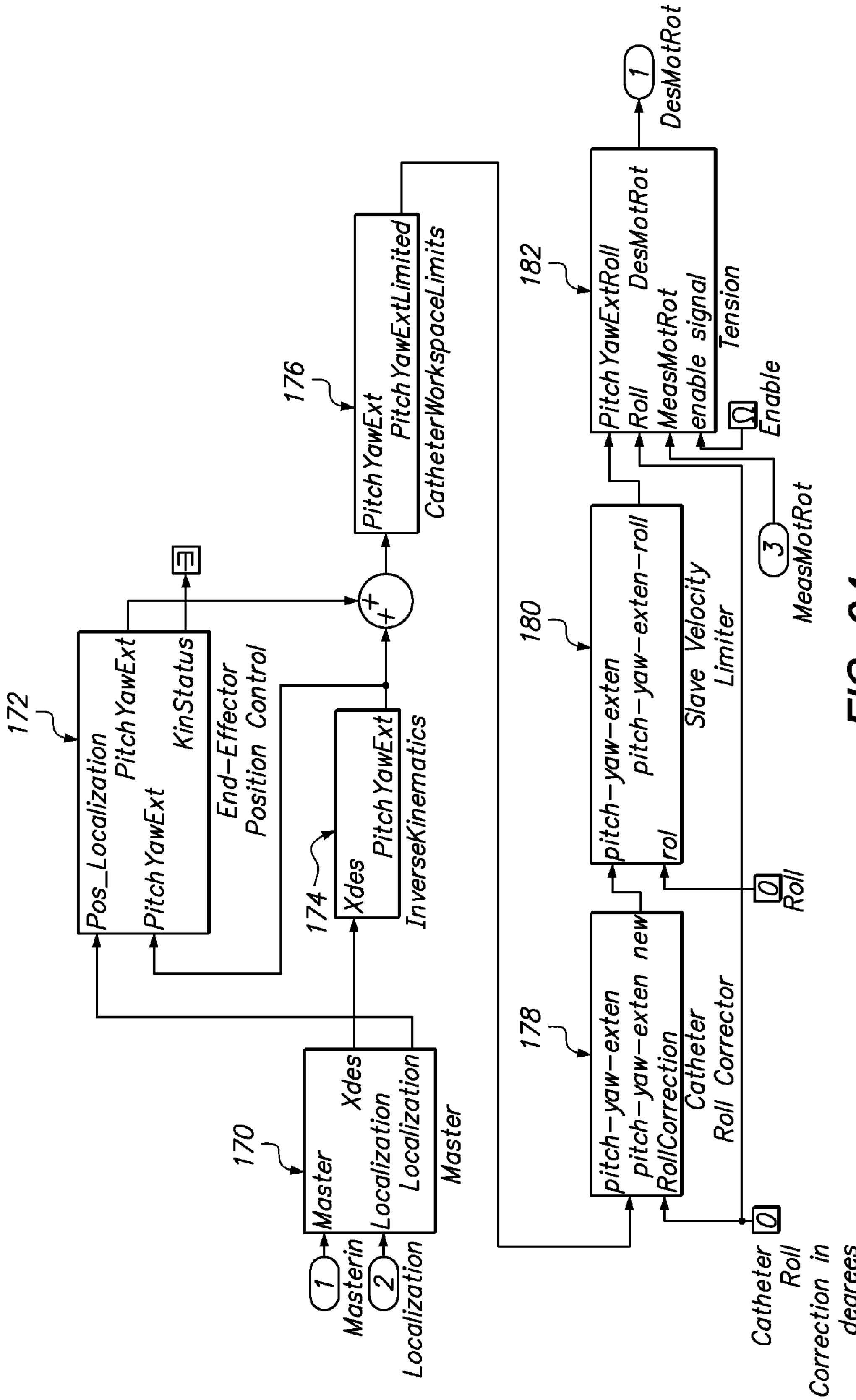

1
Masterin
2
Localization
170
Master
Xdes
Localization
Localization
Master
172
Pos_Localization
PitchYawExt
PitchYawExt
KinStatus
End-Effector
Position Control
174
Xdes
PitchYawExt
InverseKinematics
176
PitchYawExt
PitchYawExtLimited
CatheterWorkspaceLimits
178
pitch-yaw-exten
pitch-yaw-exten new
RollCorrection
Catheter
Roll Corrector
0
Catheter
Roll
Correction in
degrees
180
pitch-yaw-exten
pitch-yaw-exten-roll
rol
Slave Velocity
Limiter
0
Roll
182
PitchYawExtRoll
Roll
MeasMotRot
enable signal
DesMotRot
Tension
Enable
3
MeasMotRot
1
DesMotRot

FIG. 24

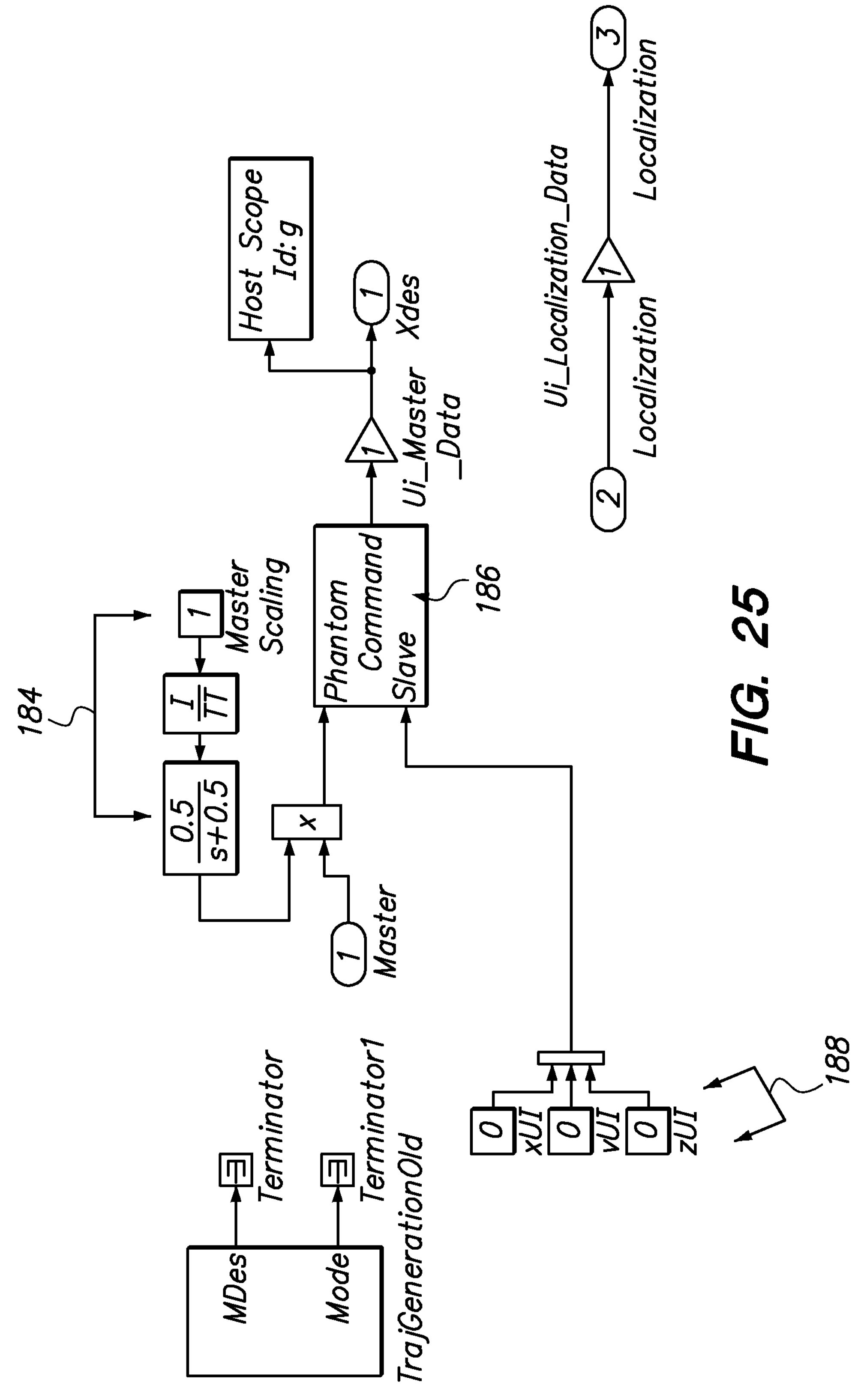

Host Scope
Id:g
1
Xdes
Ui_Master
_Data
3
Localization
Ui_Localization_Data
2
Localization
Master
Scaling
1
I
TT
0.5
s+0.5
184
Phantom
Command
Slave
186
x
1
Master
Terminator
Terminator1
MDes
Mode
TrajGenerationOld
0
xUI
0
vUI
0
zUI
188

FIG. 25

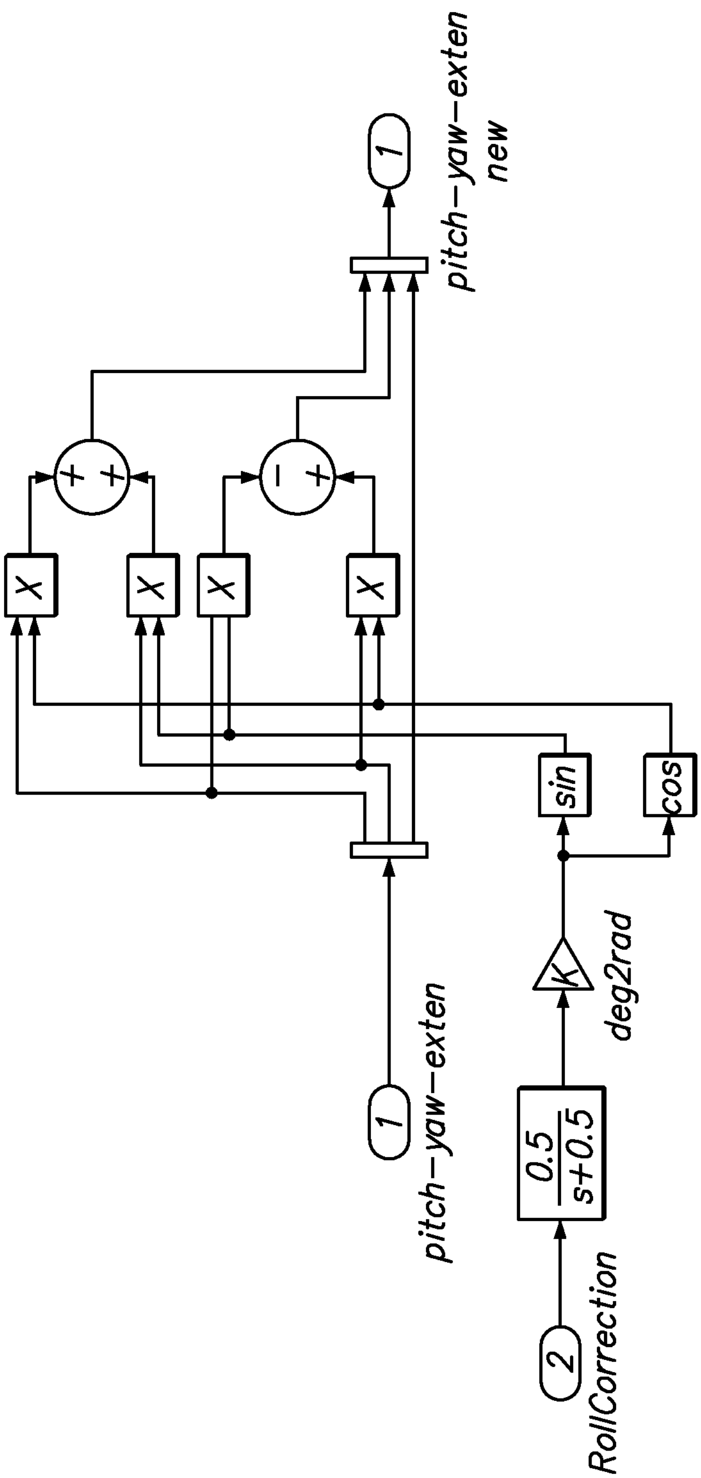

1
pitch-yaw-exten
new
X
+ +
− +
sin
cos
1
pitch-yaw-exten
K
deg2rad
0.5
s+0.5
2
RollCorrection

FIG. 26

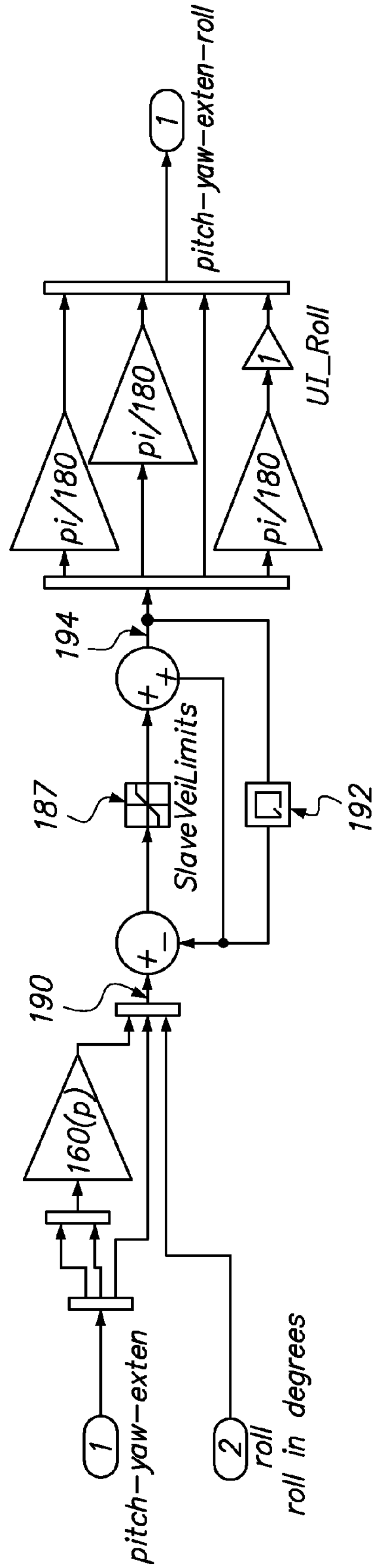
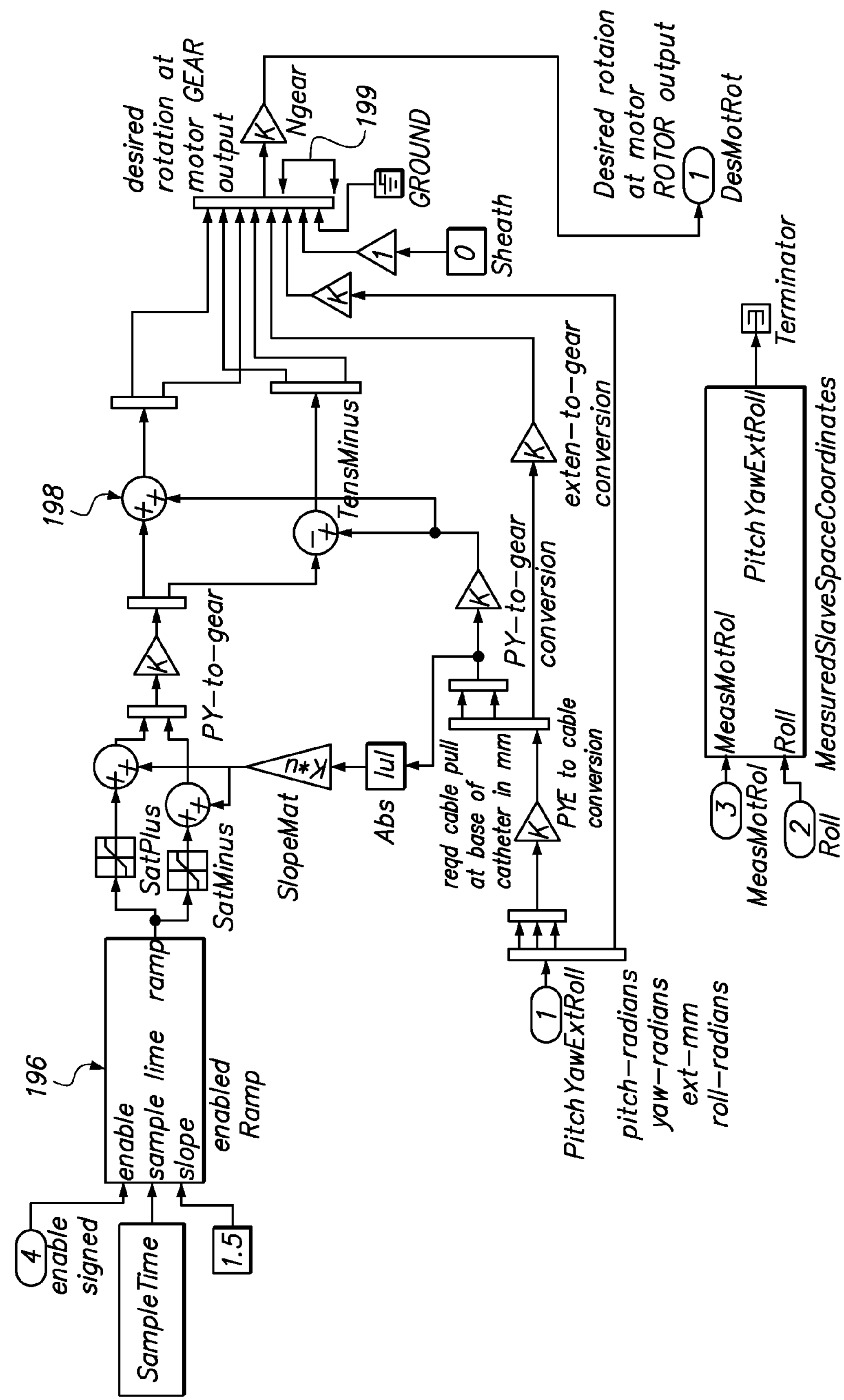

1
pitch-yaw-exten-roll
pi/180
pi/180
pi/180
1
UI_Roll
194
SlaveVeilLimits
187
192
190
160(p)
1
pitch-yaw-exten
2
roll
roll in degrees

FIG. 27



4
enable signed
SampleTime
1.5
196
enable
sample lime
slope
ramp
enabled Ramp
SatPlus
SatMinus
SlopeMat
K*u
|u|
Abs
PY-to-gear
198
TensMinus
PY-to-gear conversion
reqd cable pull at base of catheter in mm
PYE to cable conversion
exten-to-gear conversion
1
PitchYawExtRoll
pitch-radians
yaw-radians
ext-mm
roll-radians
desired rotation at motor GEAR output
Ngear
199
GROUND
0
Sheath
Desired rotaion at motor ROTOR output
1
DesMotRot
Terminator
3
MeasMotRol
2
Roll
MeasMotRol
Roll
PitchYawExtRoll
MeasuredSlaveSpaceCoordinates

FIG. 28

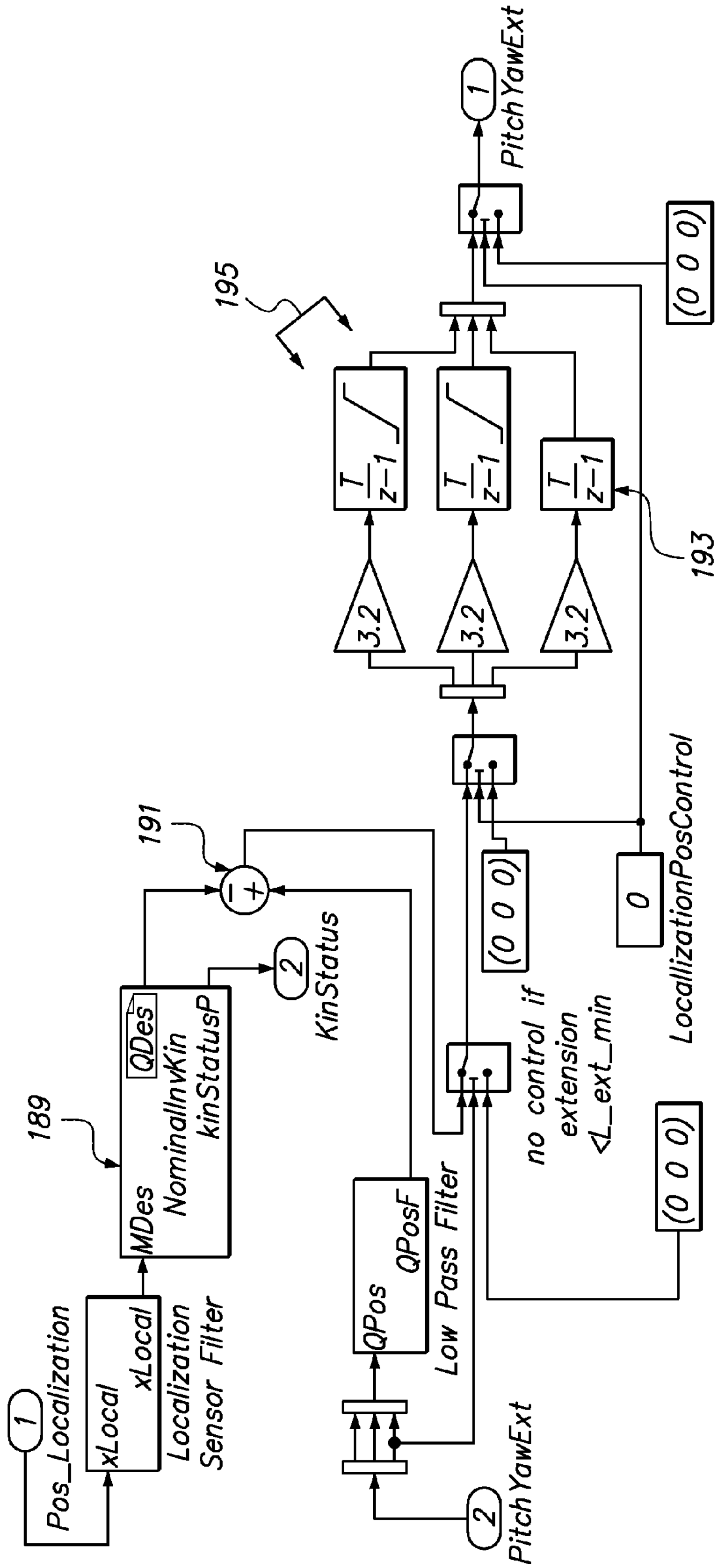

1
Pos_Localization
xLocal
xLocal
Localization
Sensor Filter
189
MDes
NominalInvKin
QDes
kinStatusP
2
KinStatus
191
2
PitchYawExt
QPos
QPosF
Low Pass Filter
no control if
extension
<L_ext_min
(0 0 0)
(0 0 0)
0
LocallizationPosControl
3.2
3.2
3.2
T
z-1
193
195
(0 0 0)
1
PitchYawExt

FIG. 29

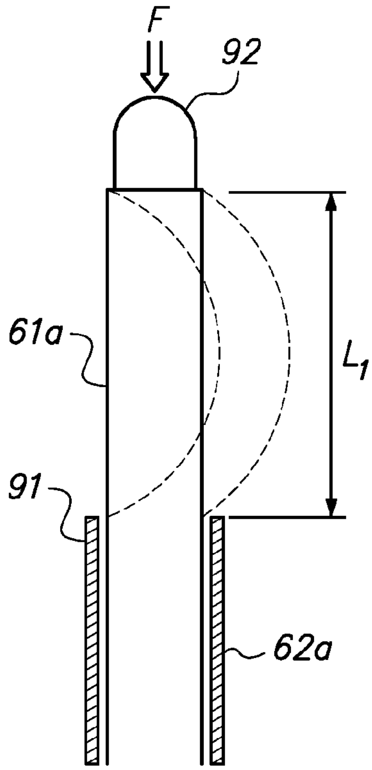


FIG. 30

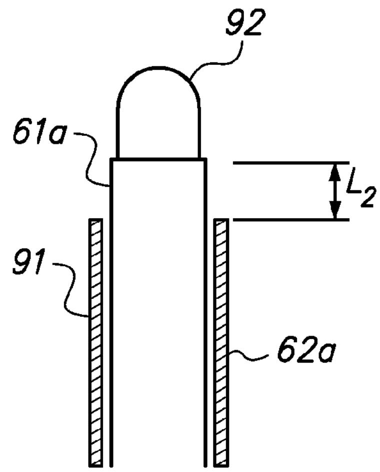


FIG. 31

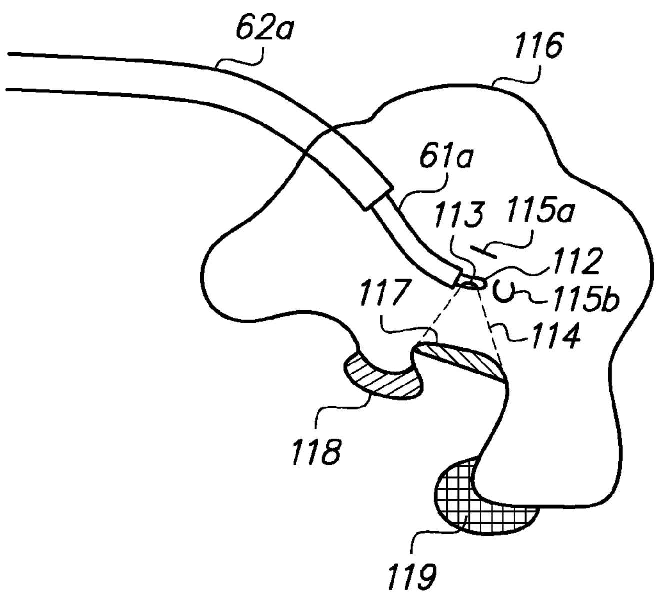
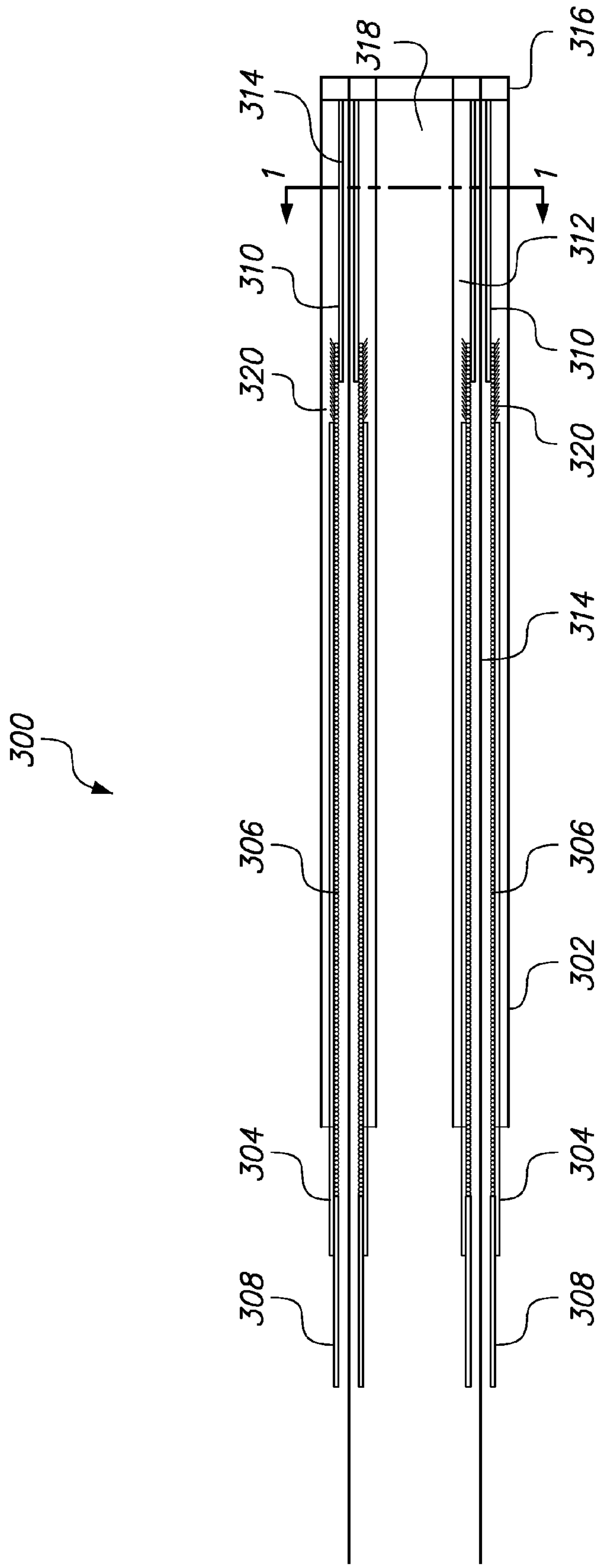


FIG. 32



318
316
314
1
1
312
310
310
320
320
314
300
306
306
302
304
304
308
308

FIG. 33A

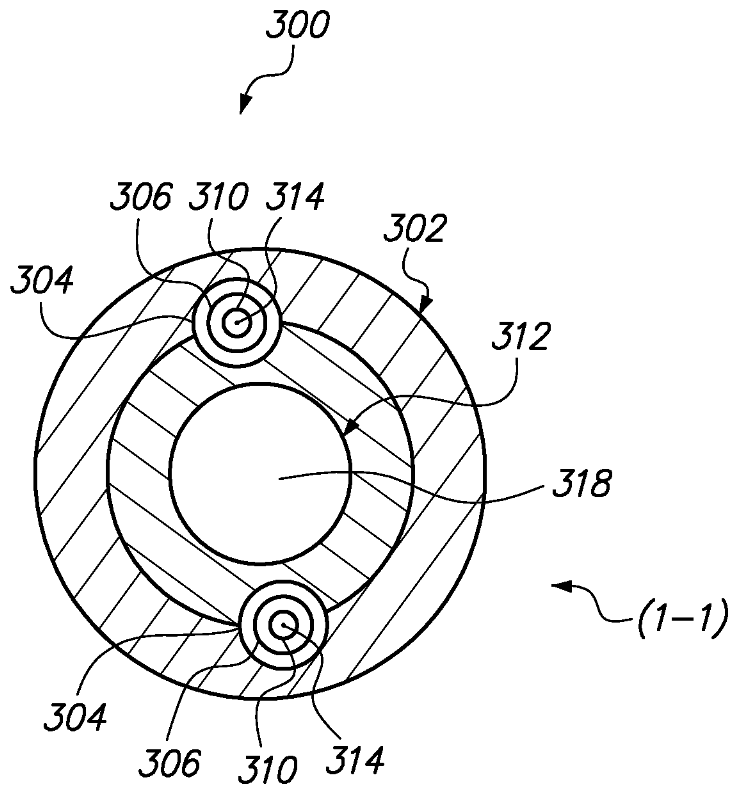


FIG. 33B

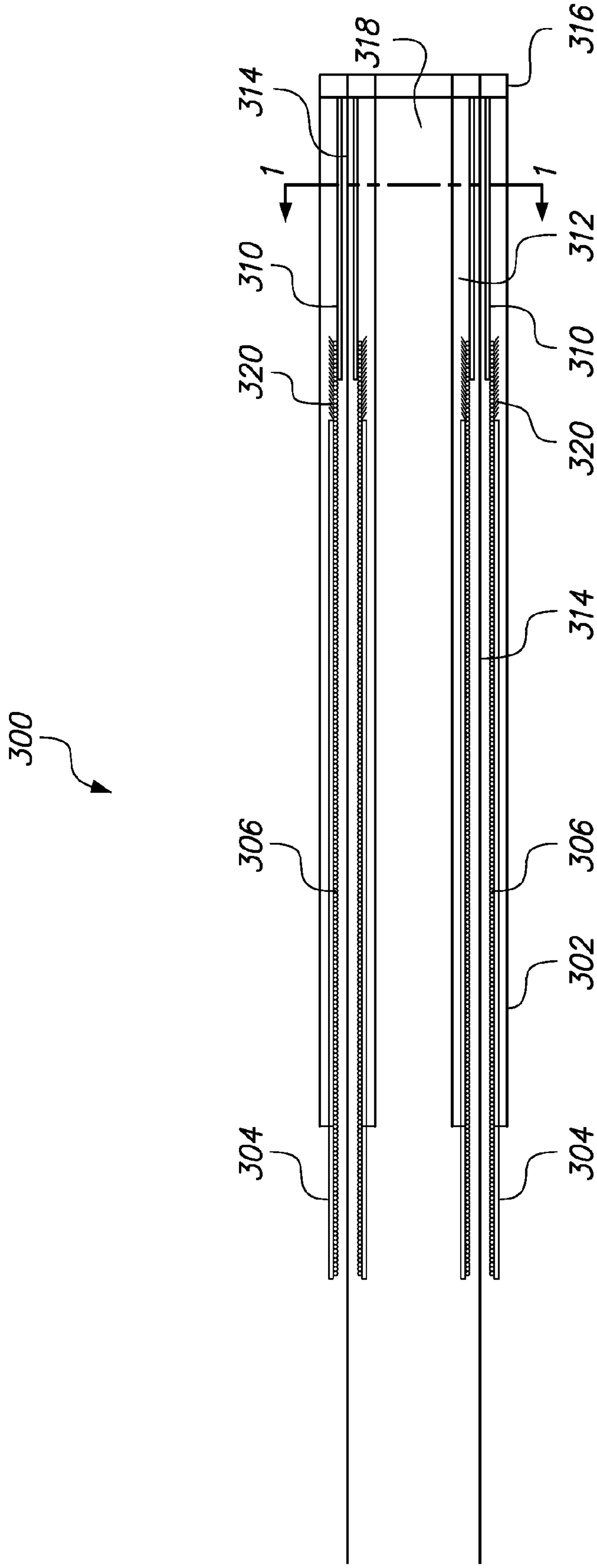


FIG. 34A

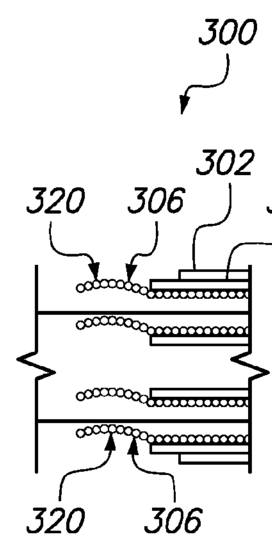


FIG. 34B

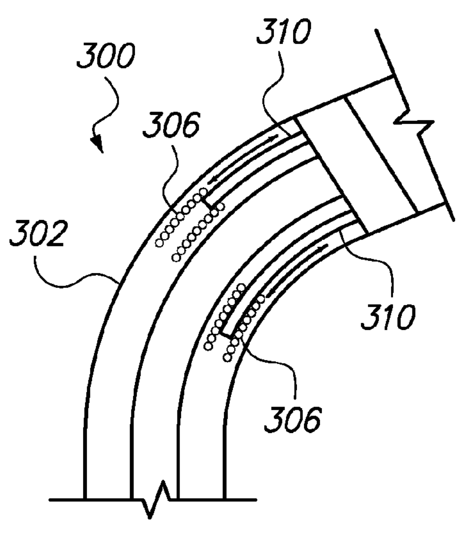


FIG. 34C

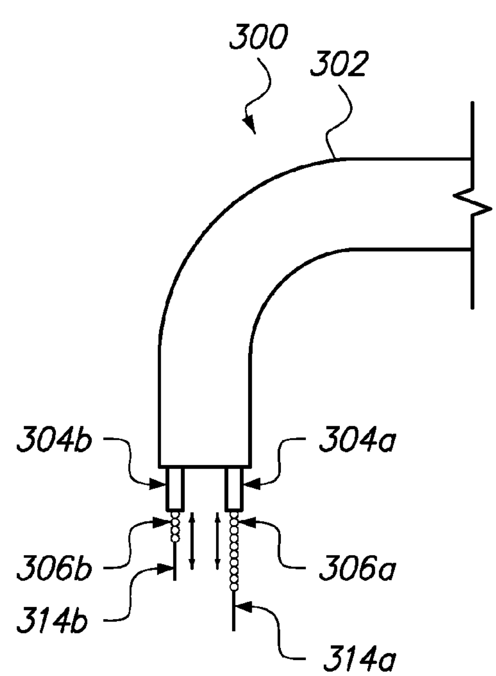


FIG. 34D

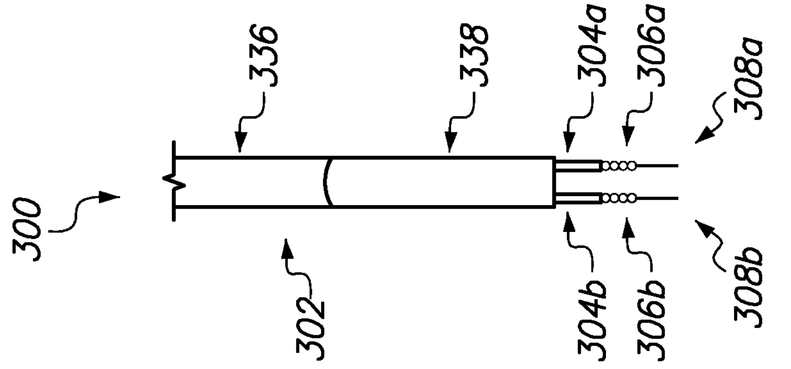


FIG. 35A

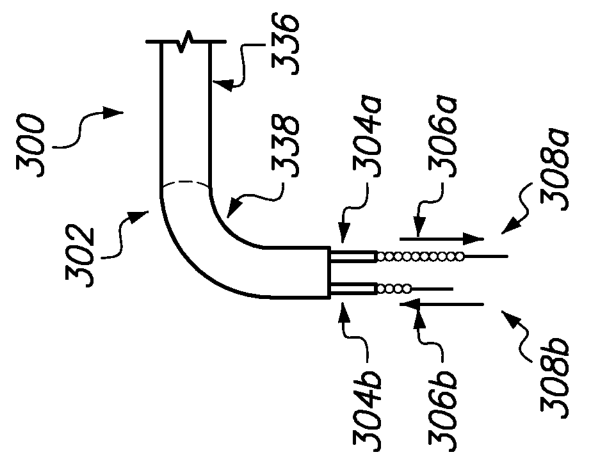


FIG. 35B

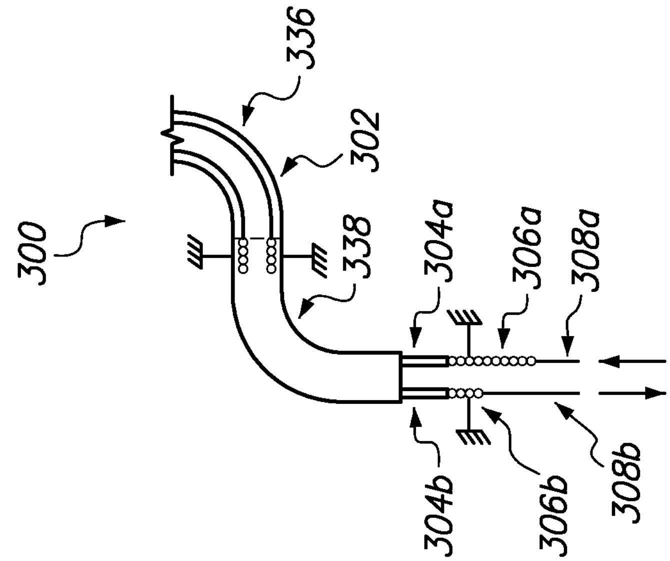


FIG. 35C

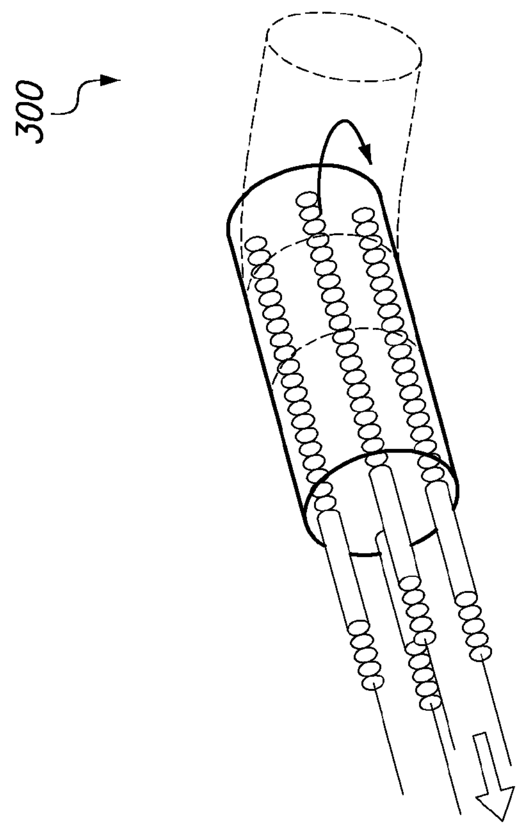


FIG. 36B

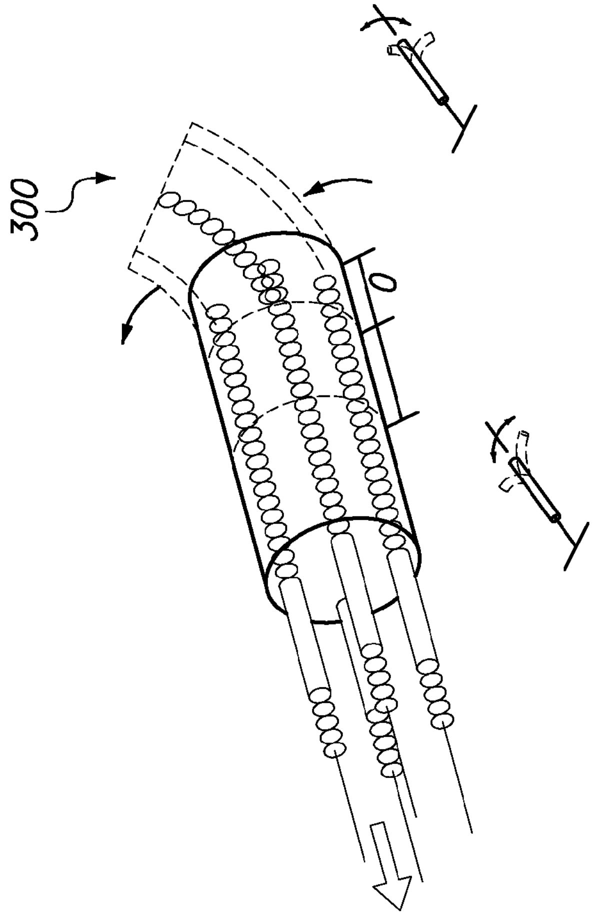


FIG. 36A

Curve Alignment Phenomenon:

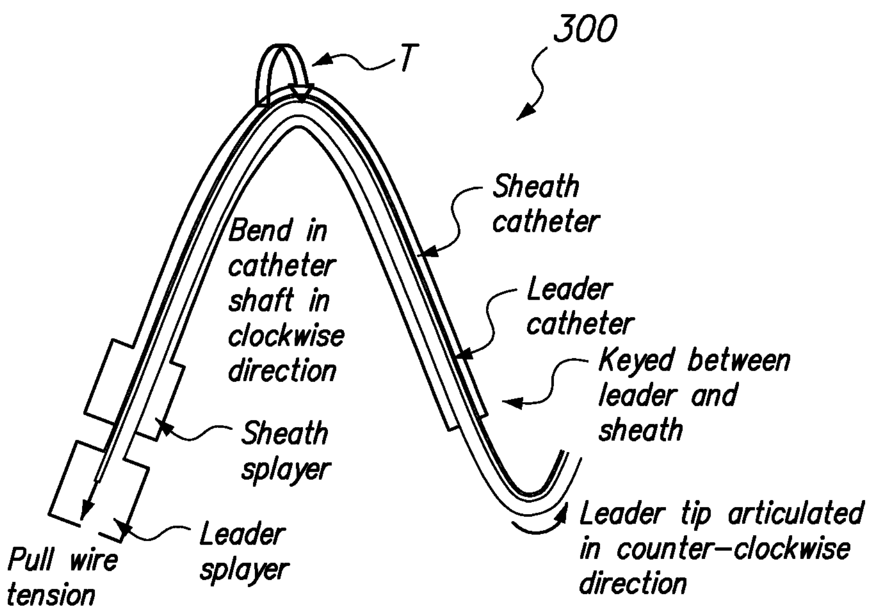


FIG. 36C

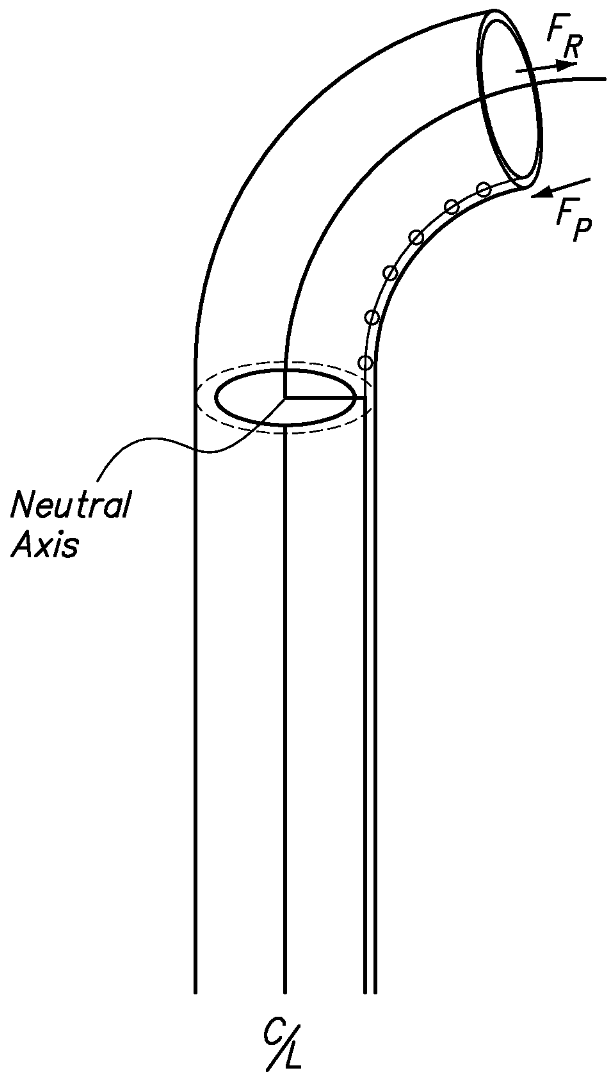


FIG. 36D

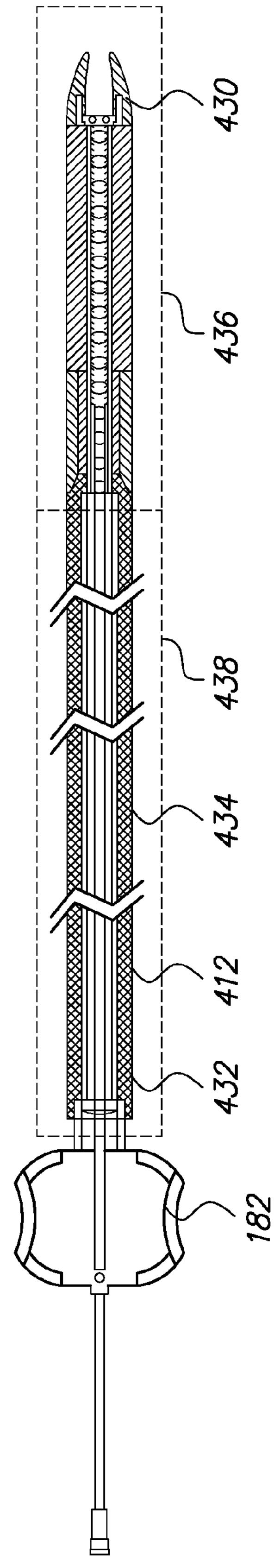


FIG. 37A

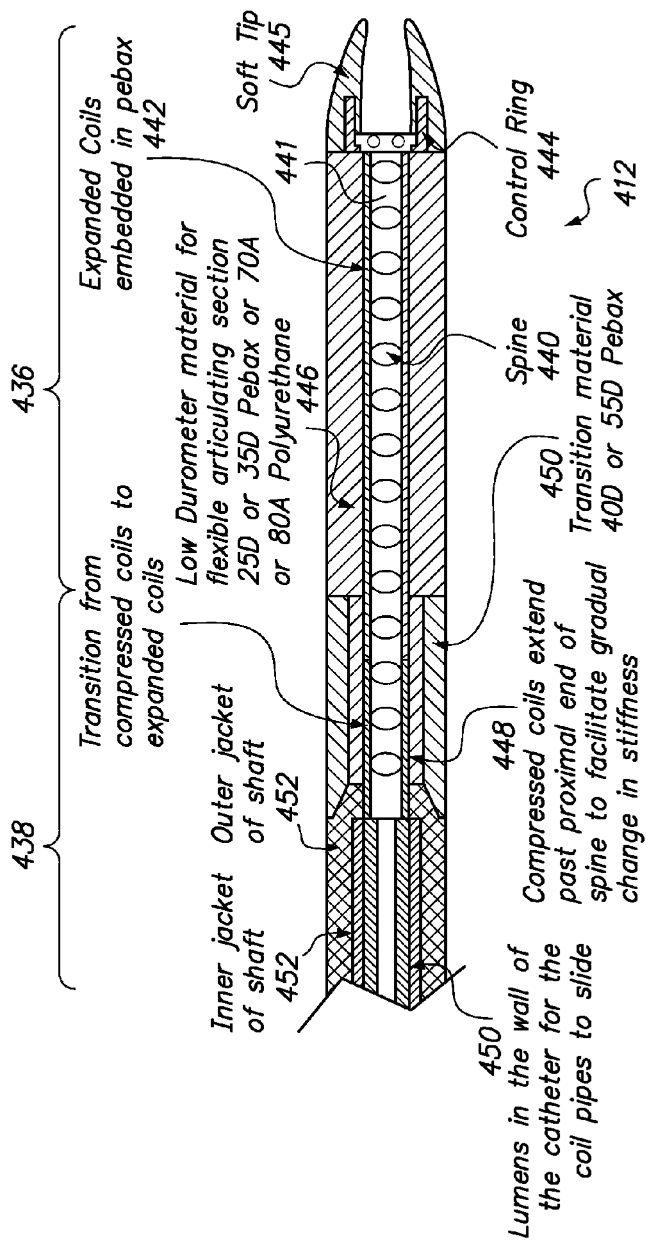


FIG. 37B

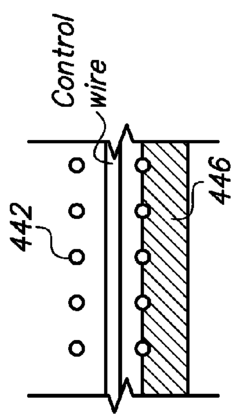


FIG. 37C

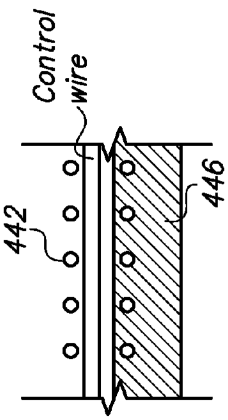


FIG. 37D

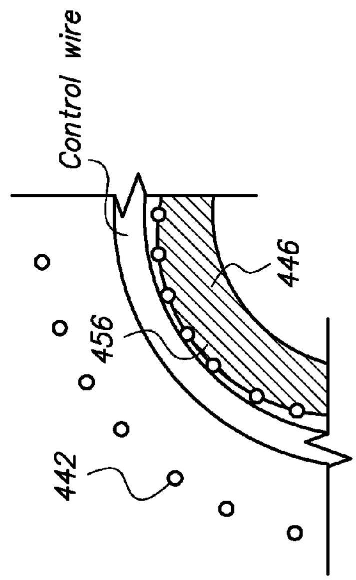
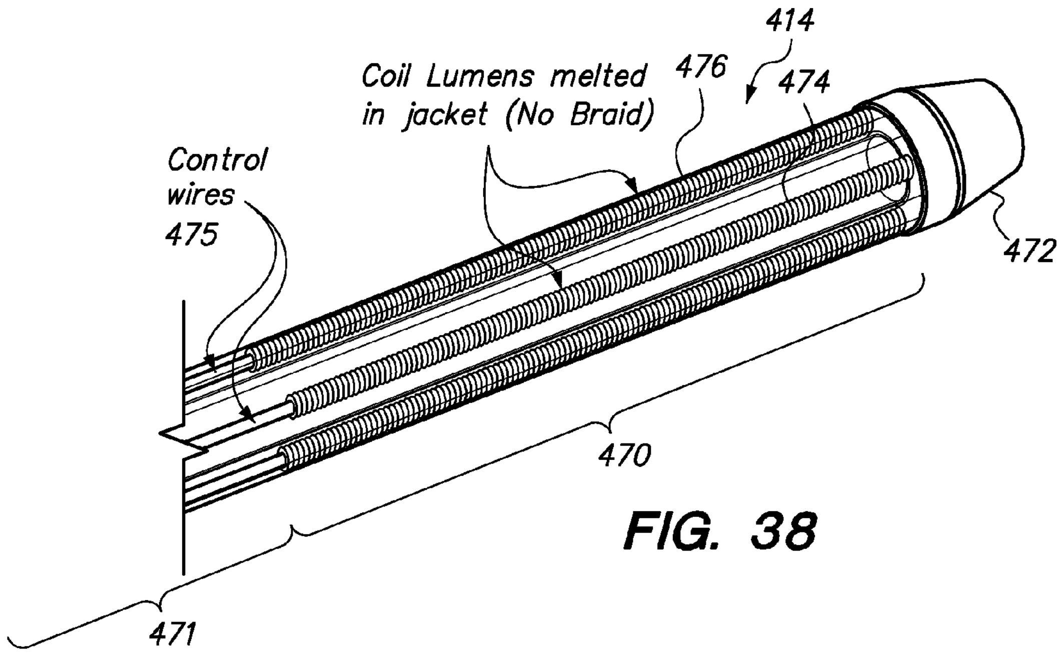
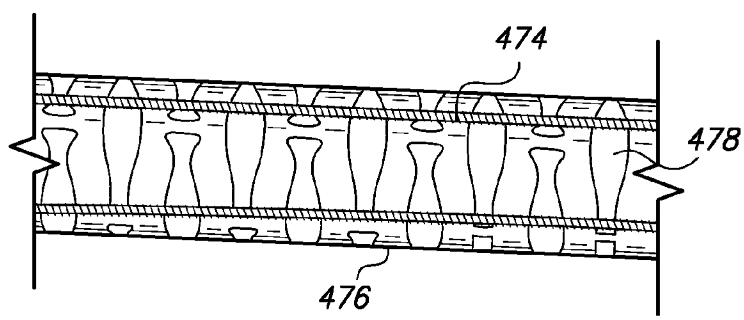


FIG. 37E



414
476
474
Coil Lumens melted in jacket (No Braid)
Control wires 475
472
470
471

FIG. 38



474
478
476

FIG. 39

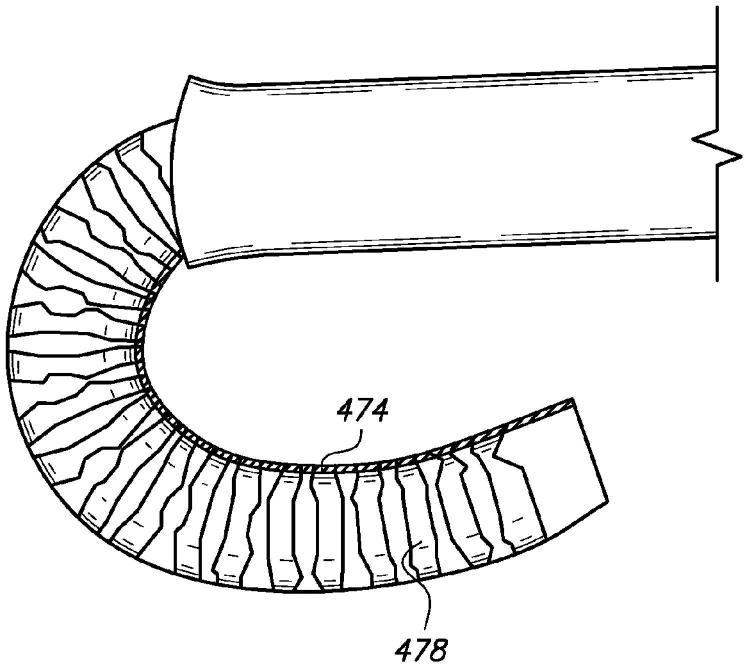


FIG. 40

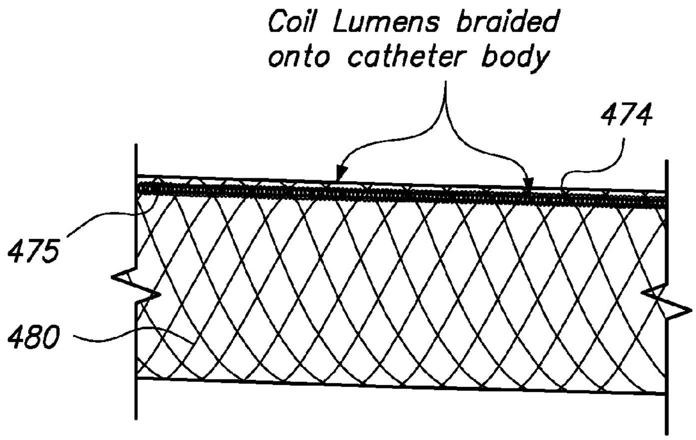


FIG. 41

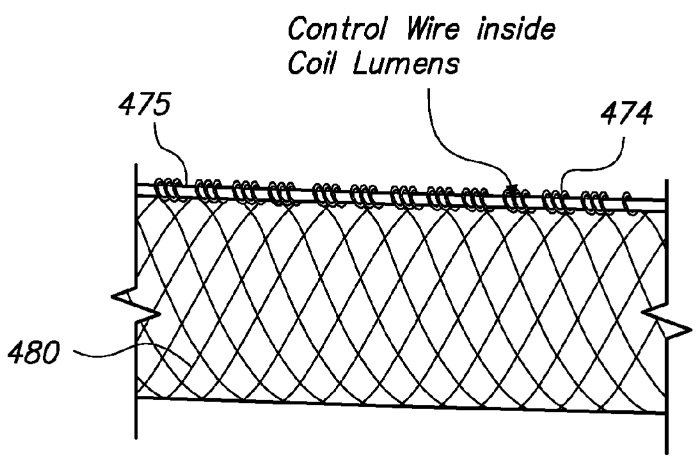


FIG. 42

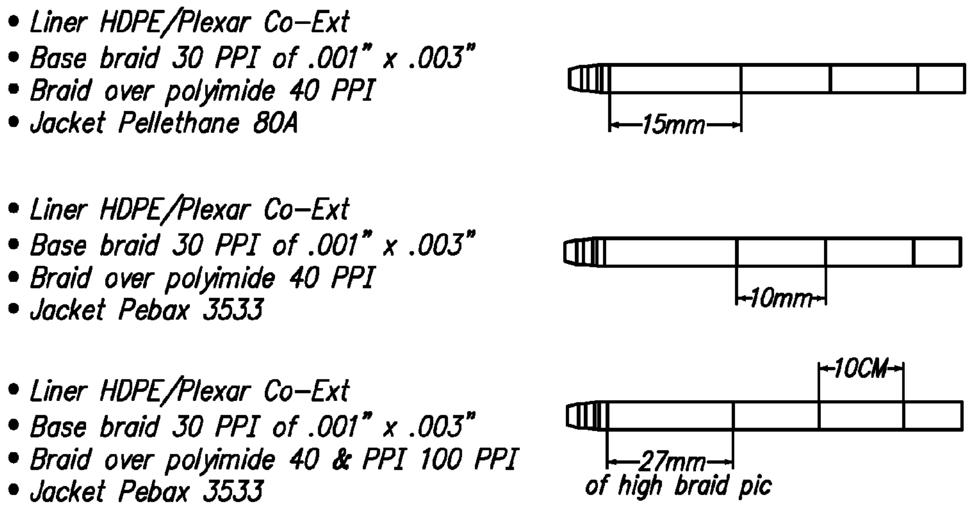

• Liner HDPE/Plexar Co-Ext
• Base braid 30 PPI of .001" x .003"
• Braid over polyimide 40 PPI
• Jacket Pellethane 80A
15mm
• Liner HDPE/Plexar Co-Ext
• Base braid 30 PPI of .001" x .003"
• Braid over polyimide 40 PPI
• Jacket Pebax 3533
10mm
• Liner HDPE/Plexar Co-Ext
• Base braid 30 PPI of .001" x .003"
• Braid over polyimide 40 & PPI 100 PPI
• Jacket Pebax 3533
10CM
27mm
of high braid pic

FIG. 43

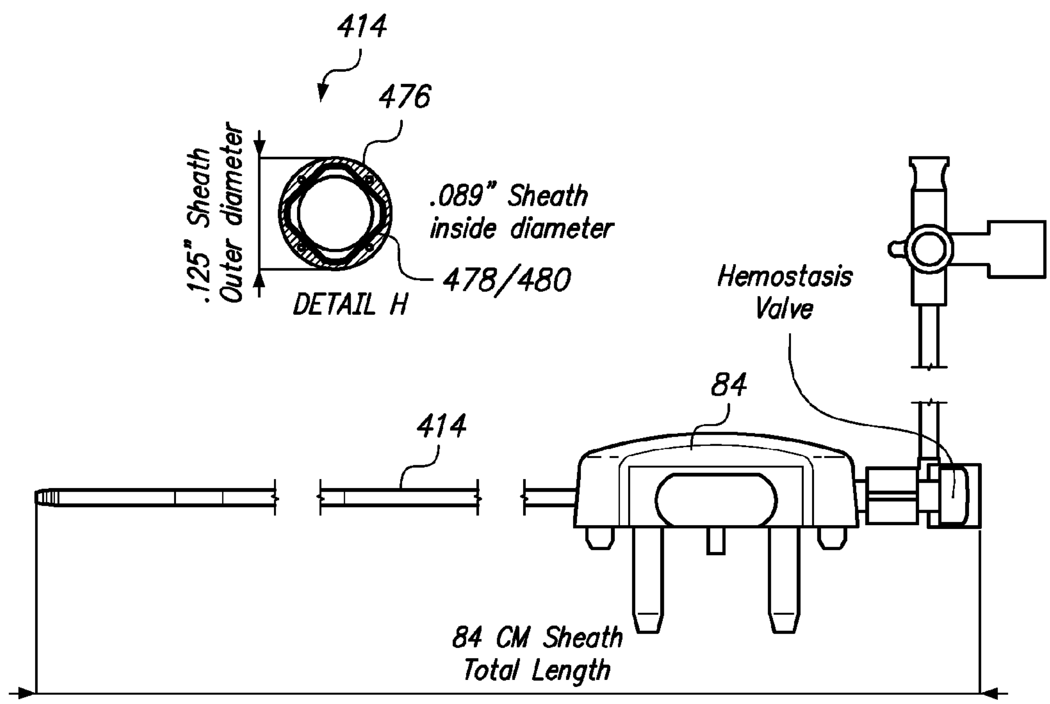

414
476
.125" Sheath
Outer diameter
.089" Sheath
inside diameter
478/480
DETAIL H
Hemostasis
Valve
84
414
84 CM Sheath
Total Length

FIG. 44

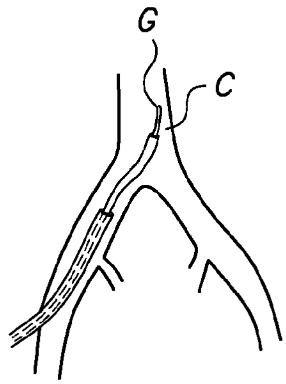


FIG. 45

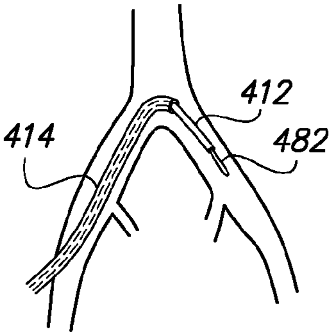


FIG. 46

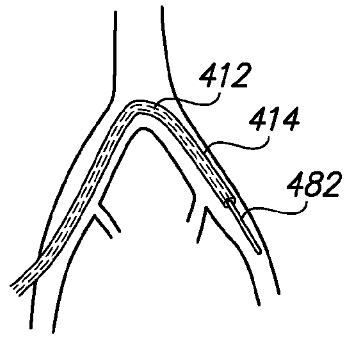


FIG. 47

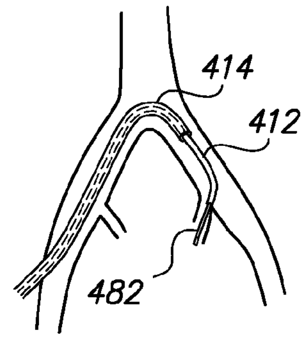


FIG. 48

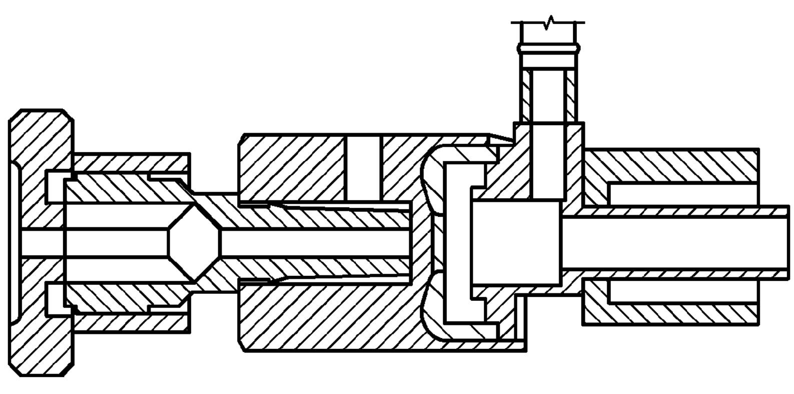


FIG. 49

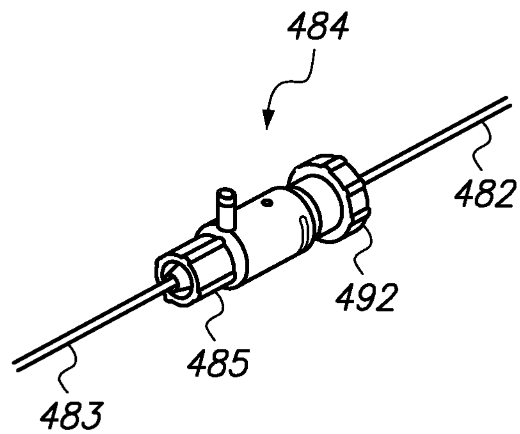


FIG. 50A

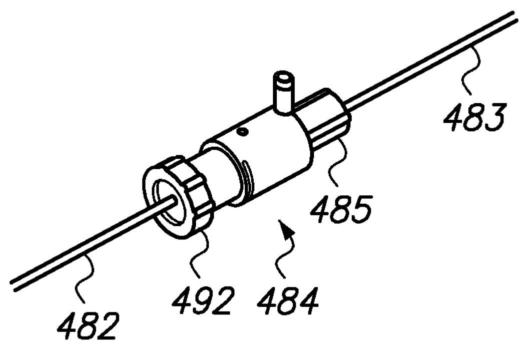


FIG. 50B

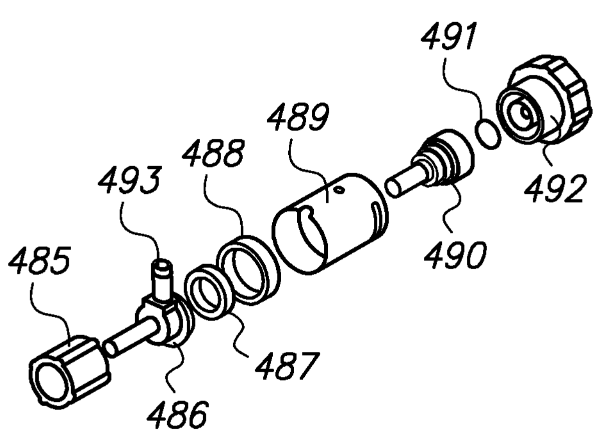


FIG. 50C

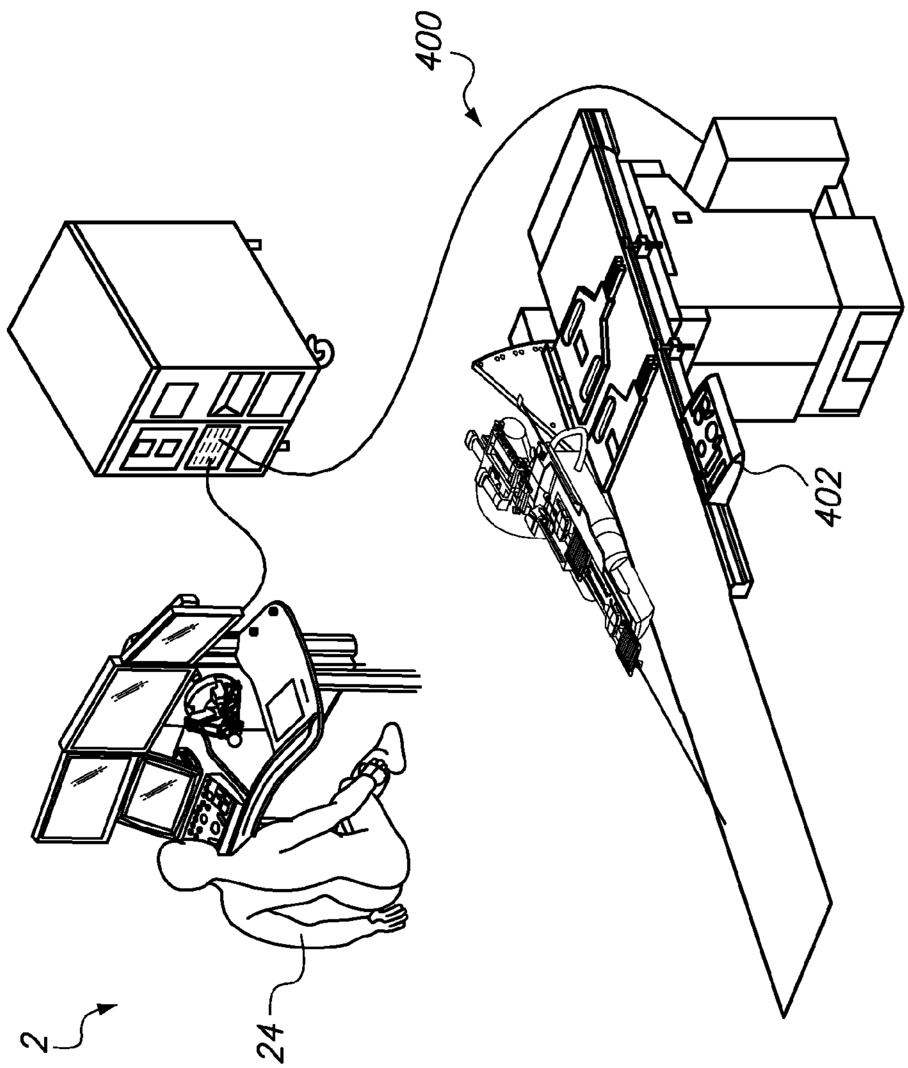


FIG. 51A

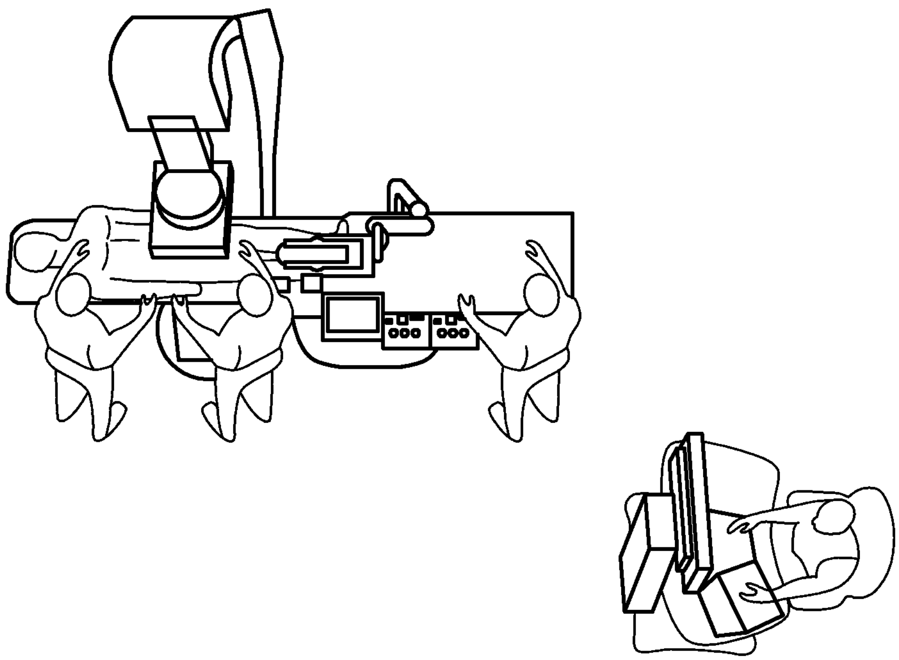


FIG. 51B

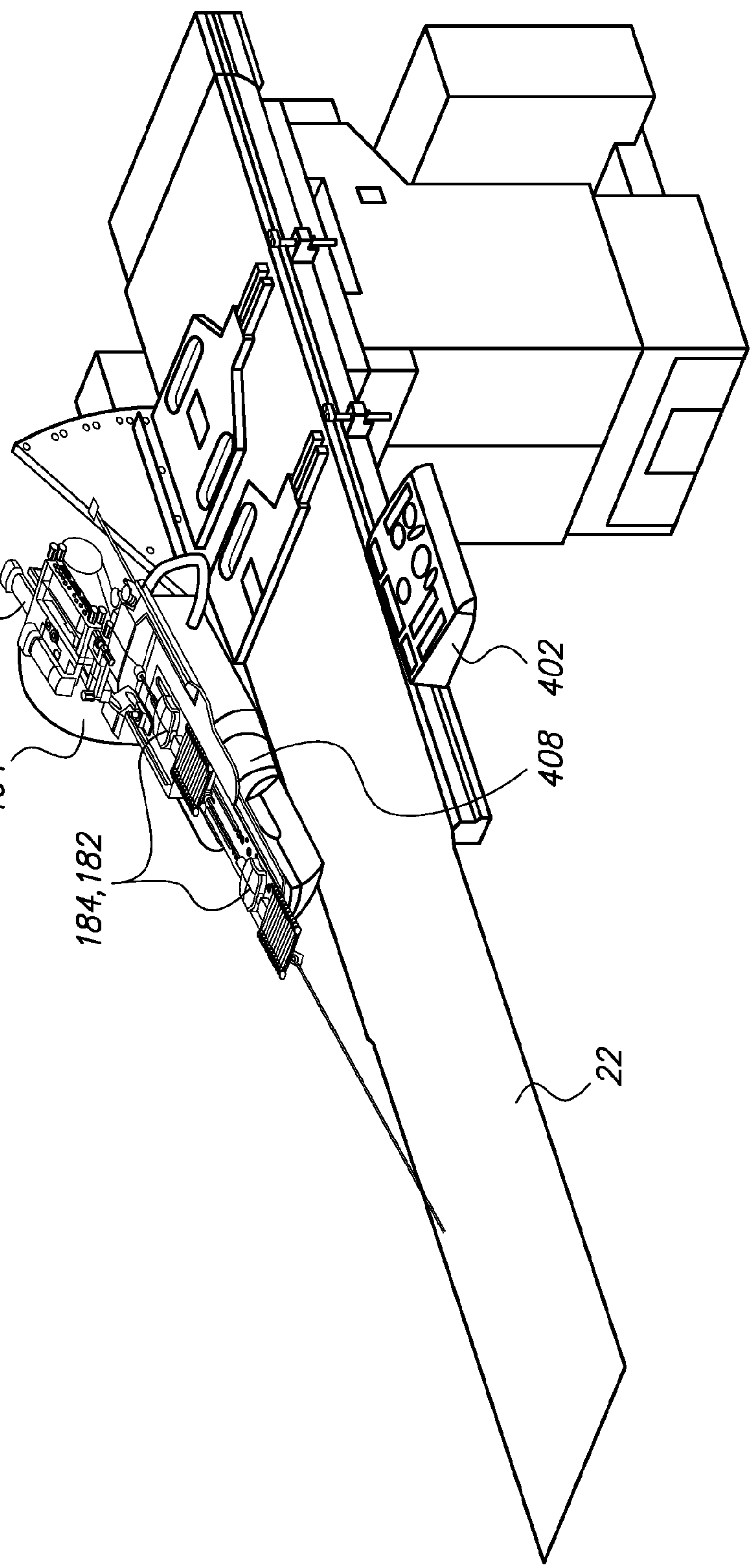


FIG. 51C

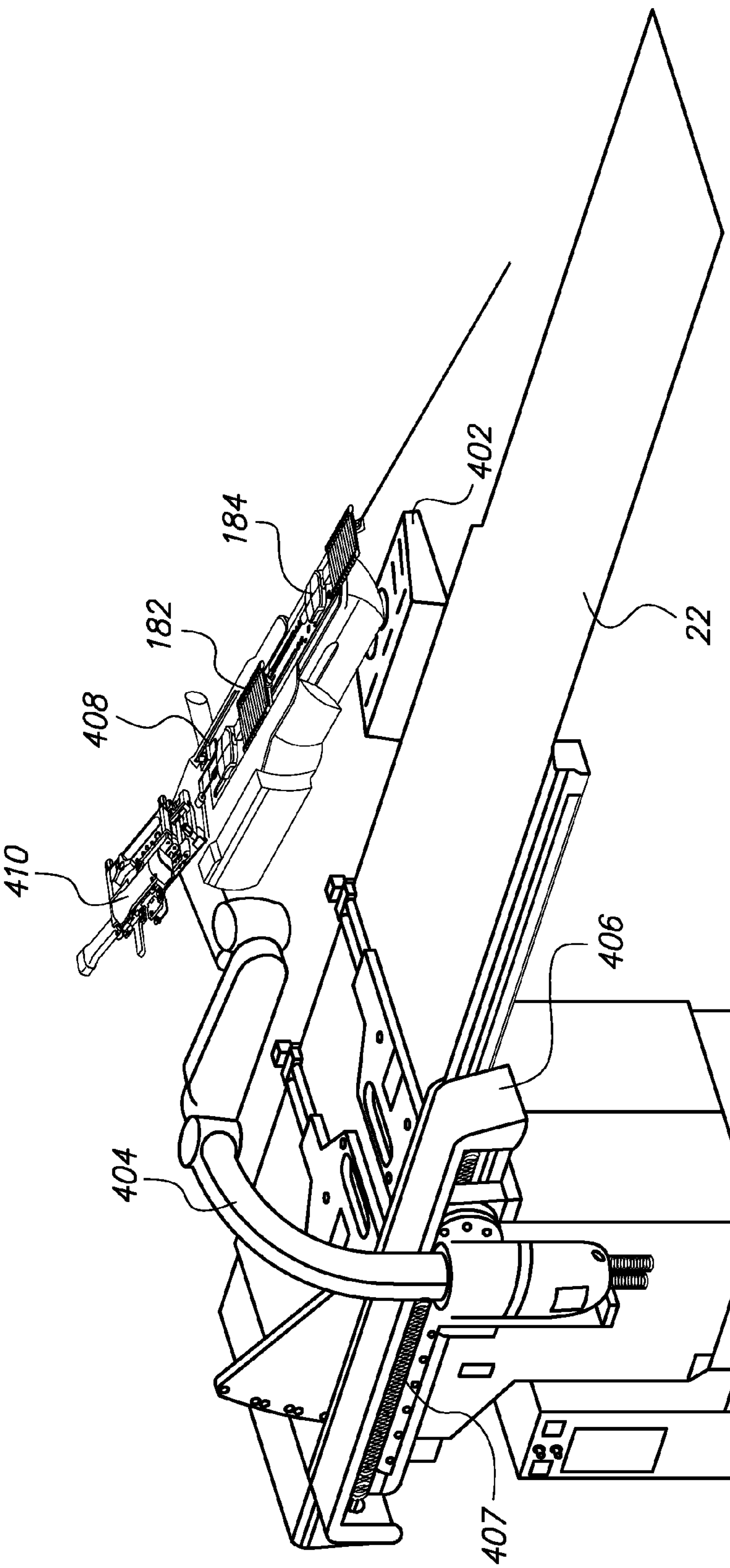


FIG. 51D

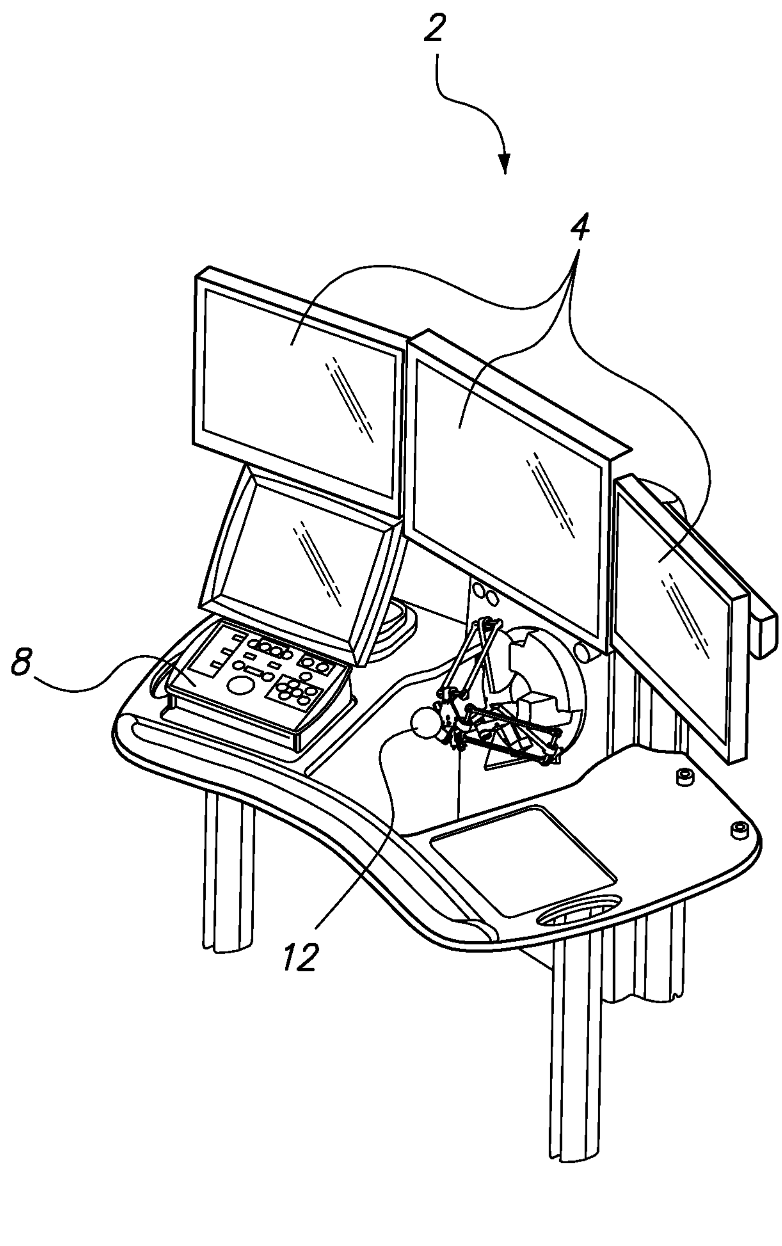


FIG. 51E

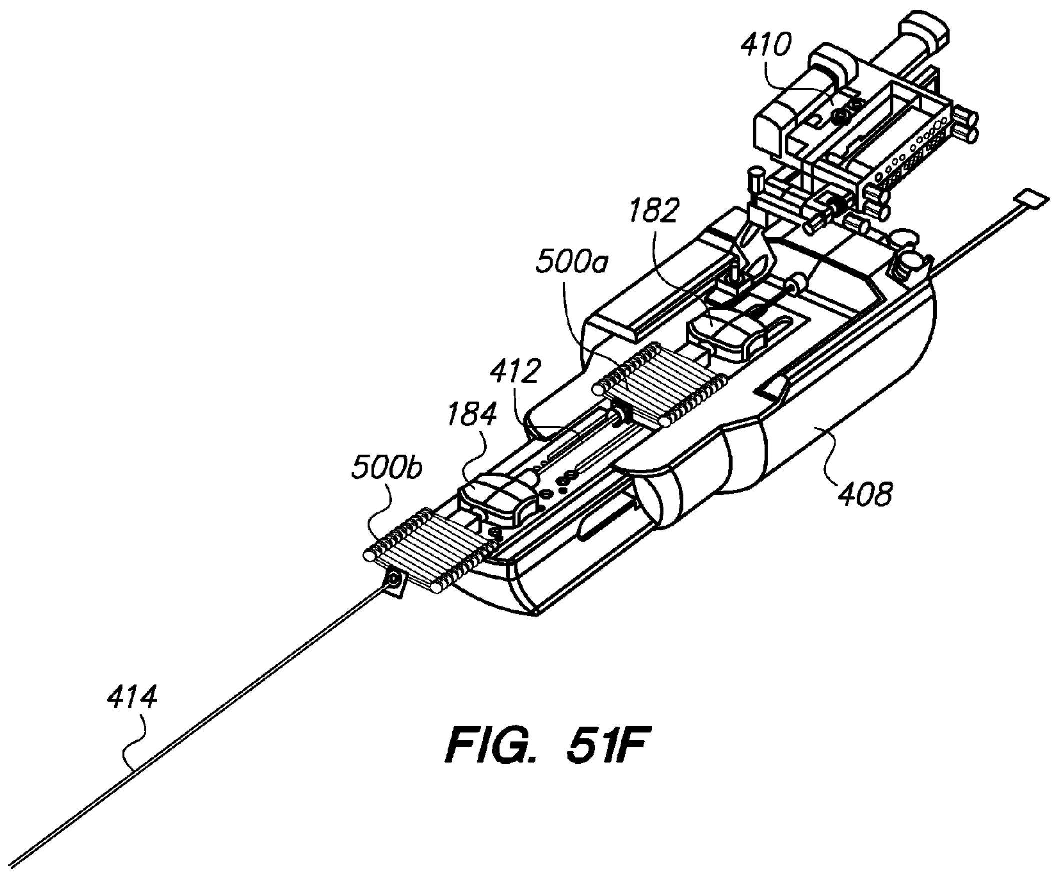


FIG. 51F

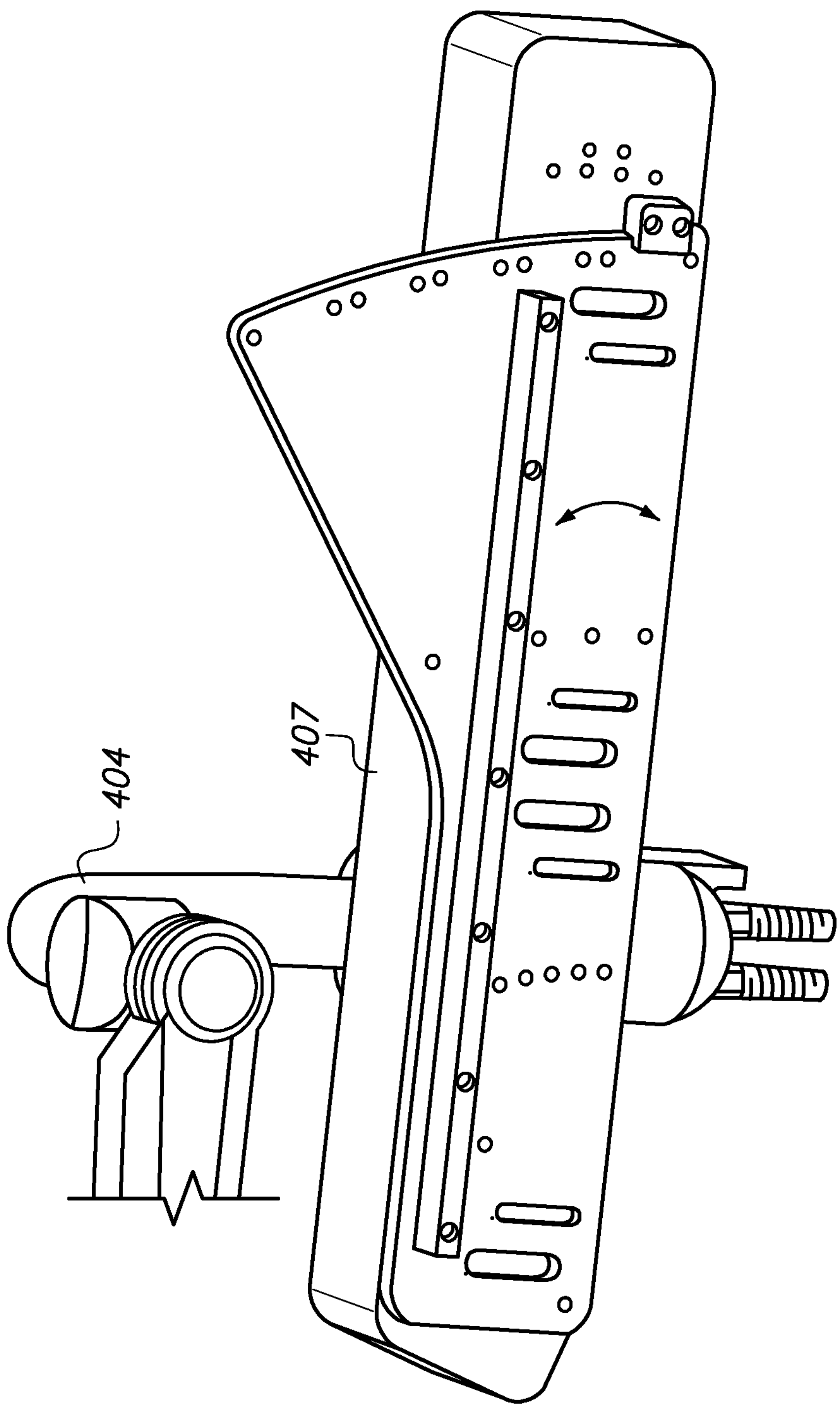


FIG. 51G

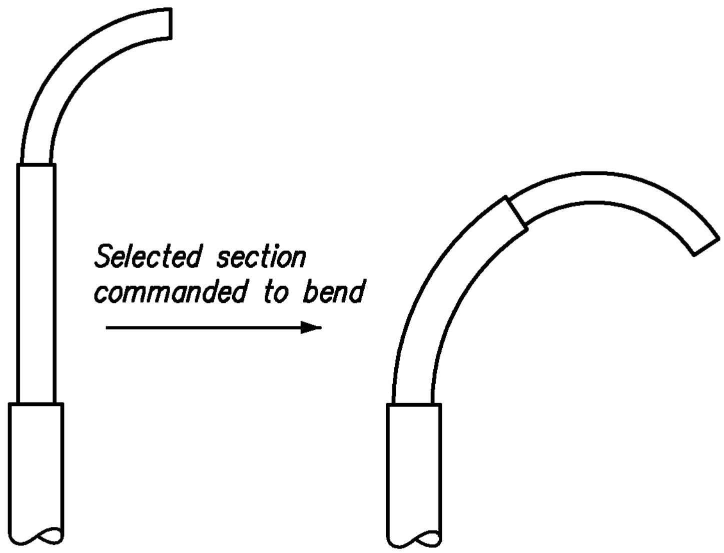


FIG. 52A

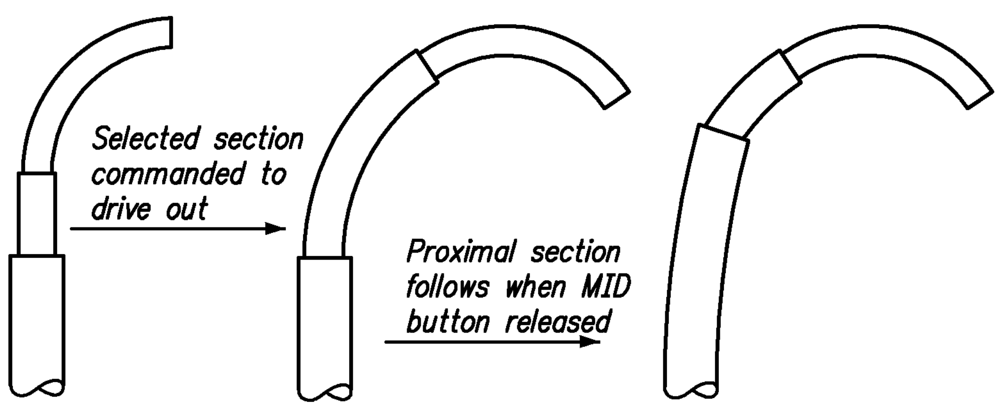


FIG. 52B

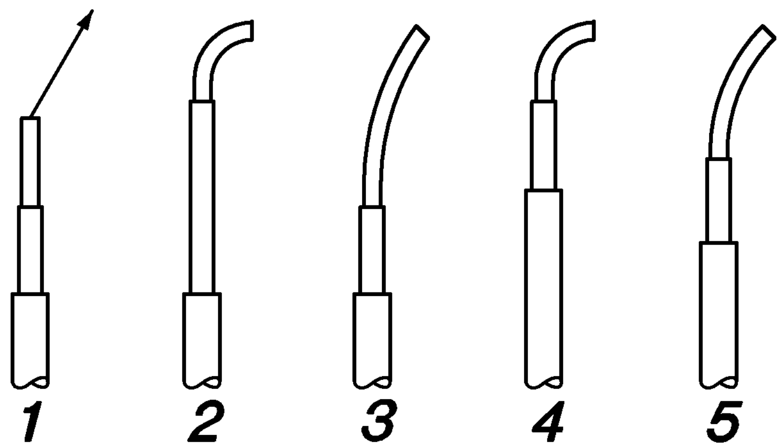


FIG. 52C

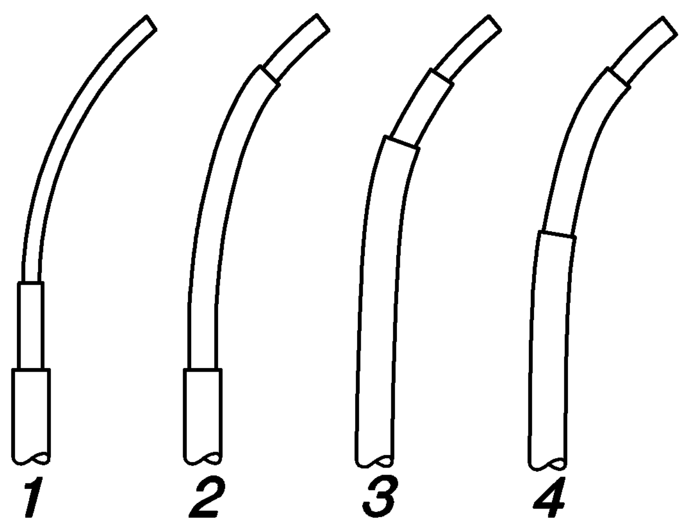


FIG. 52D

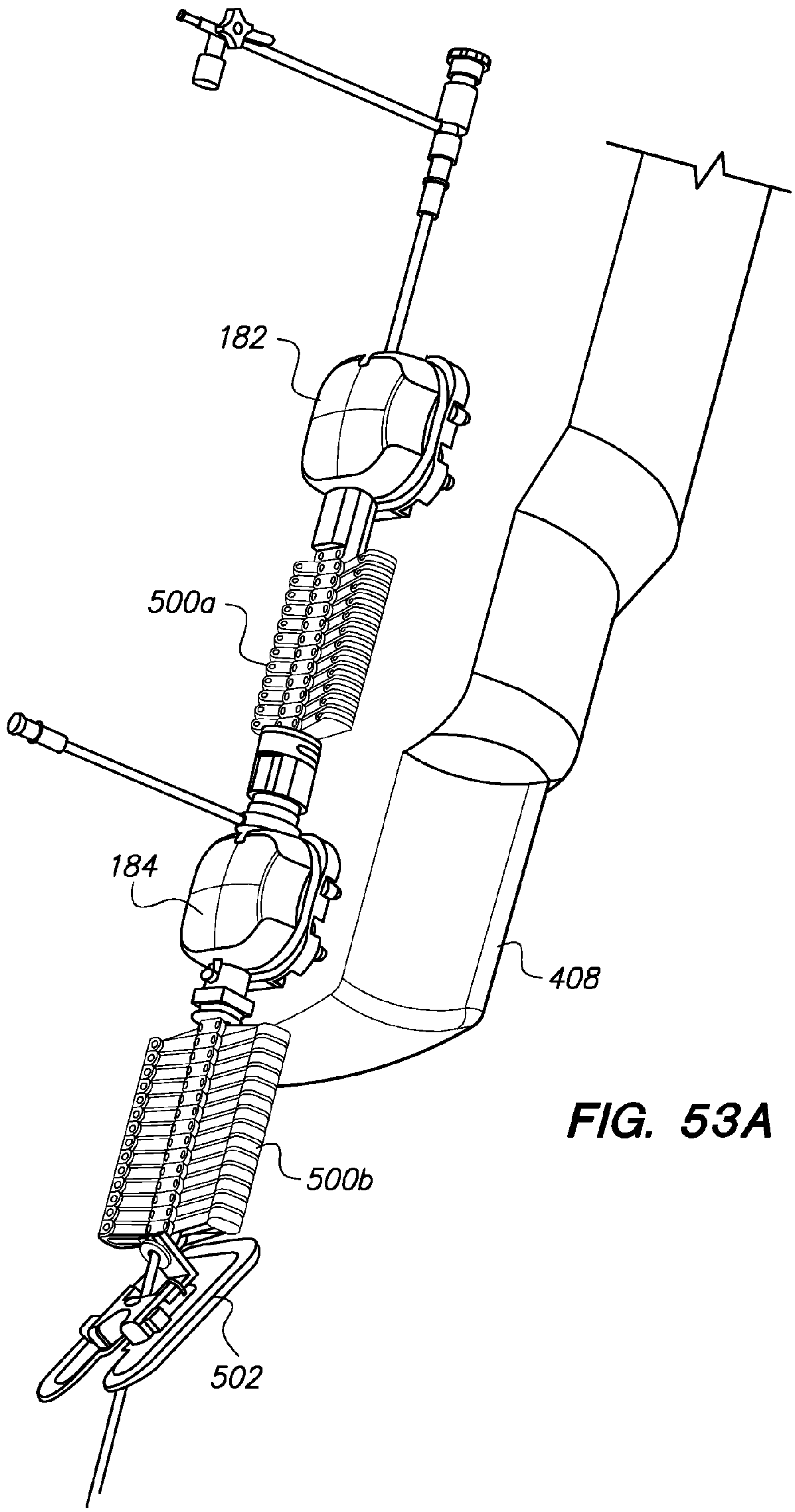


FIG. 53A

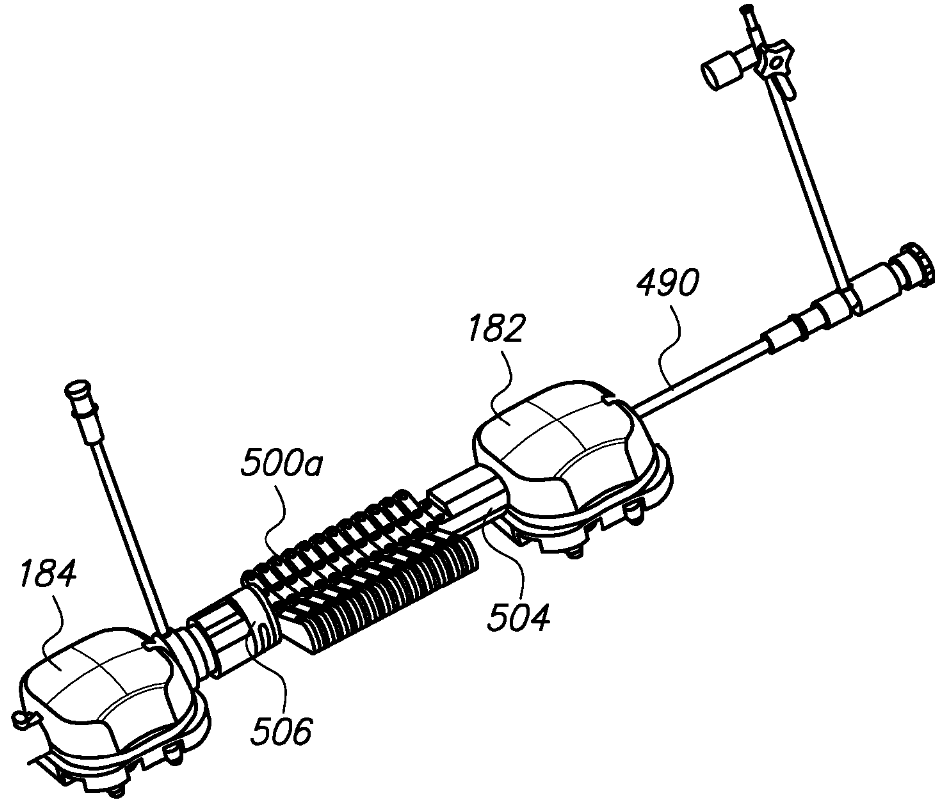


FIG. 53B

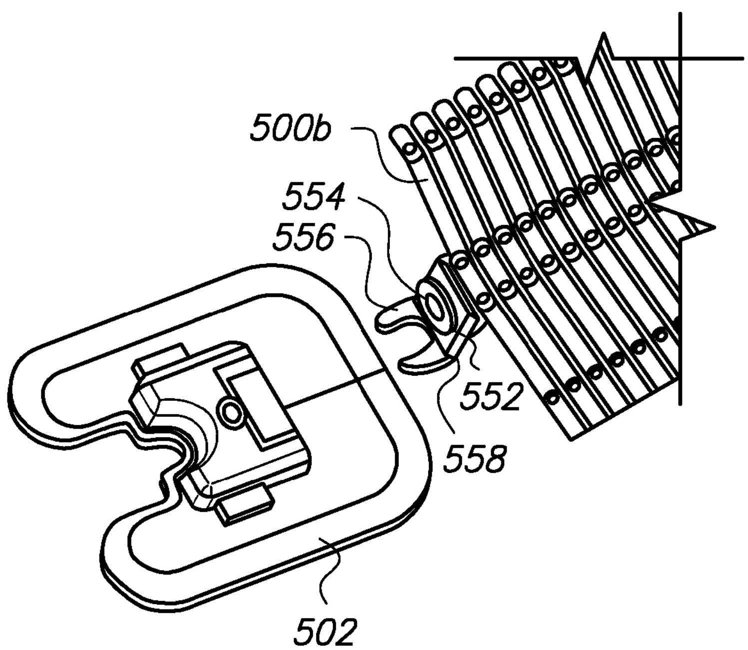


FIG. 53G

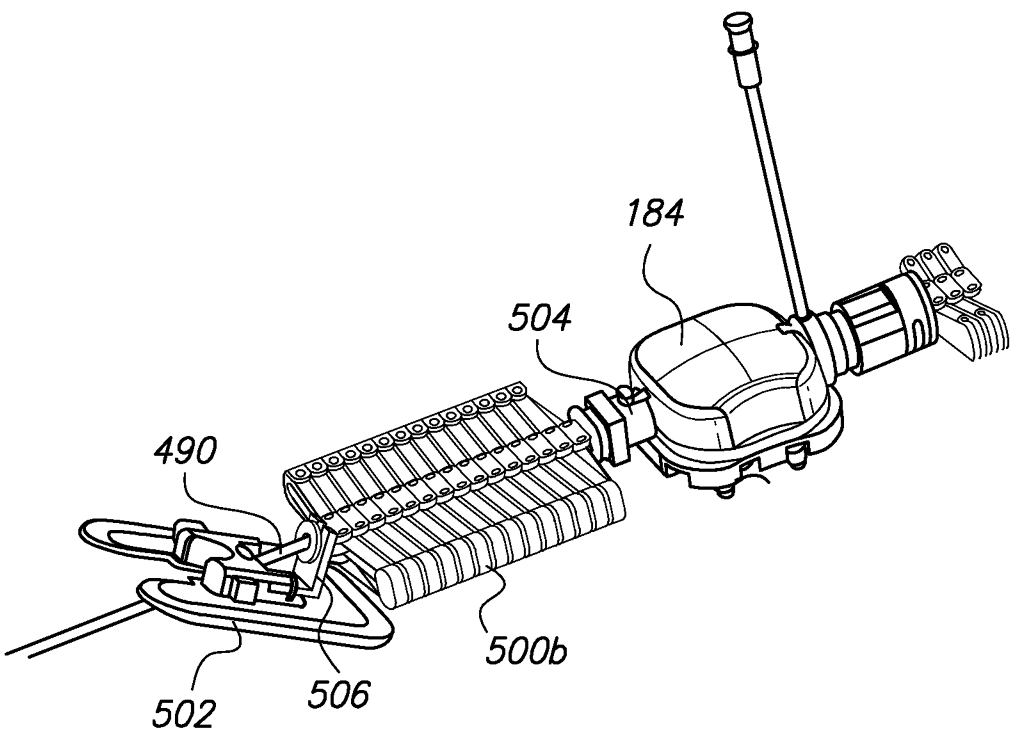


FIG. 53C

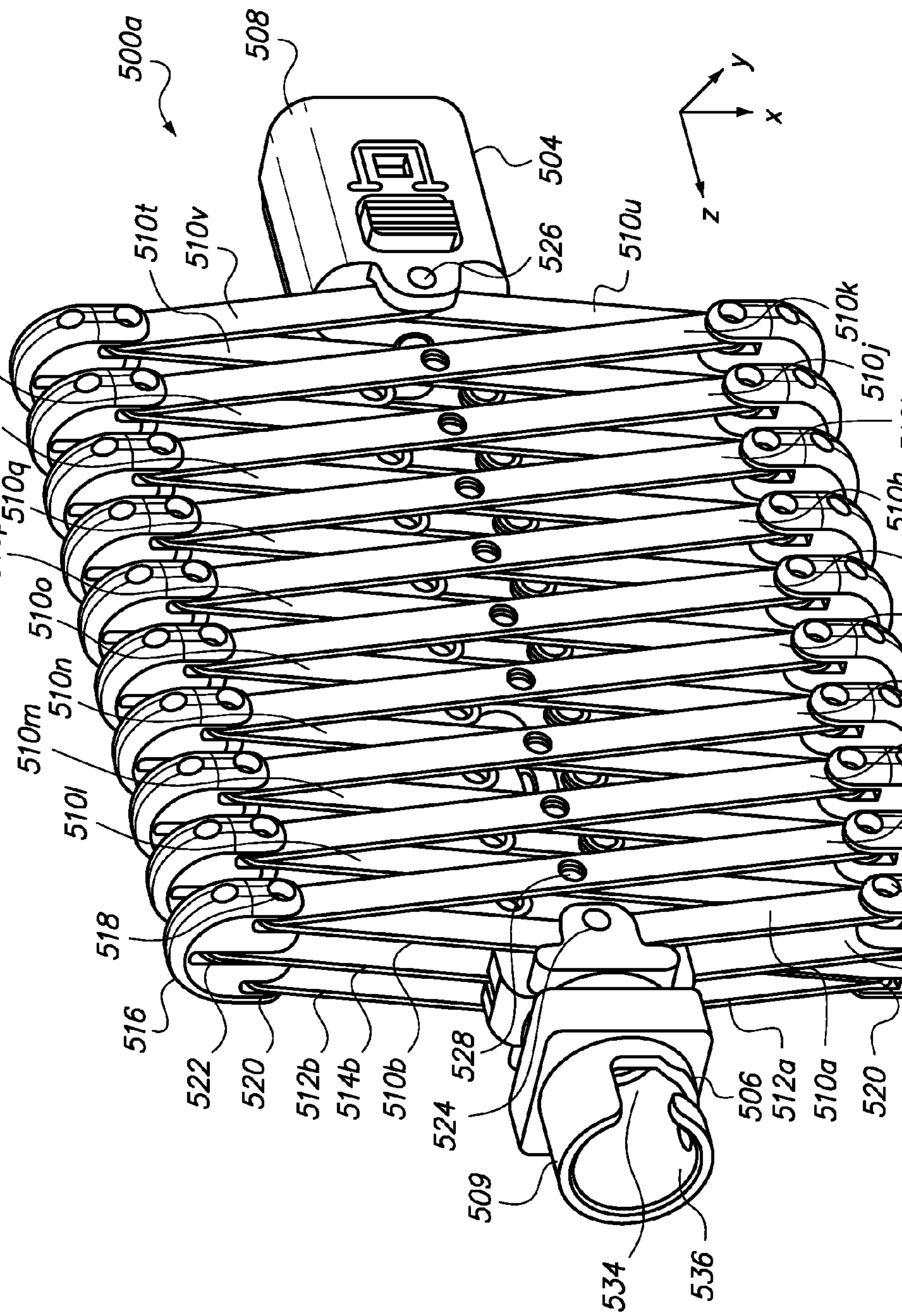

500a
508
504
526
510t
510v
510u
510s
510r
510q
510p
510o
510n
510m
510l
510k
510j
510i
510h
510g
510f
510e
510d
510c
518
516
522
520
512b
514b
510b
528
524
509
506
512a
510a
514a
534
536
x
y
z

FIG. 53D

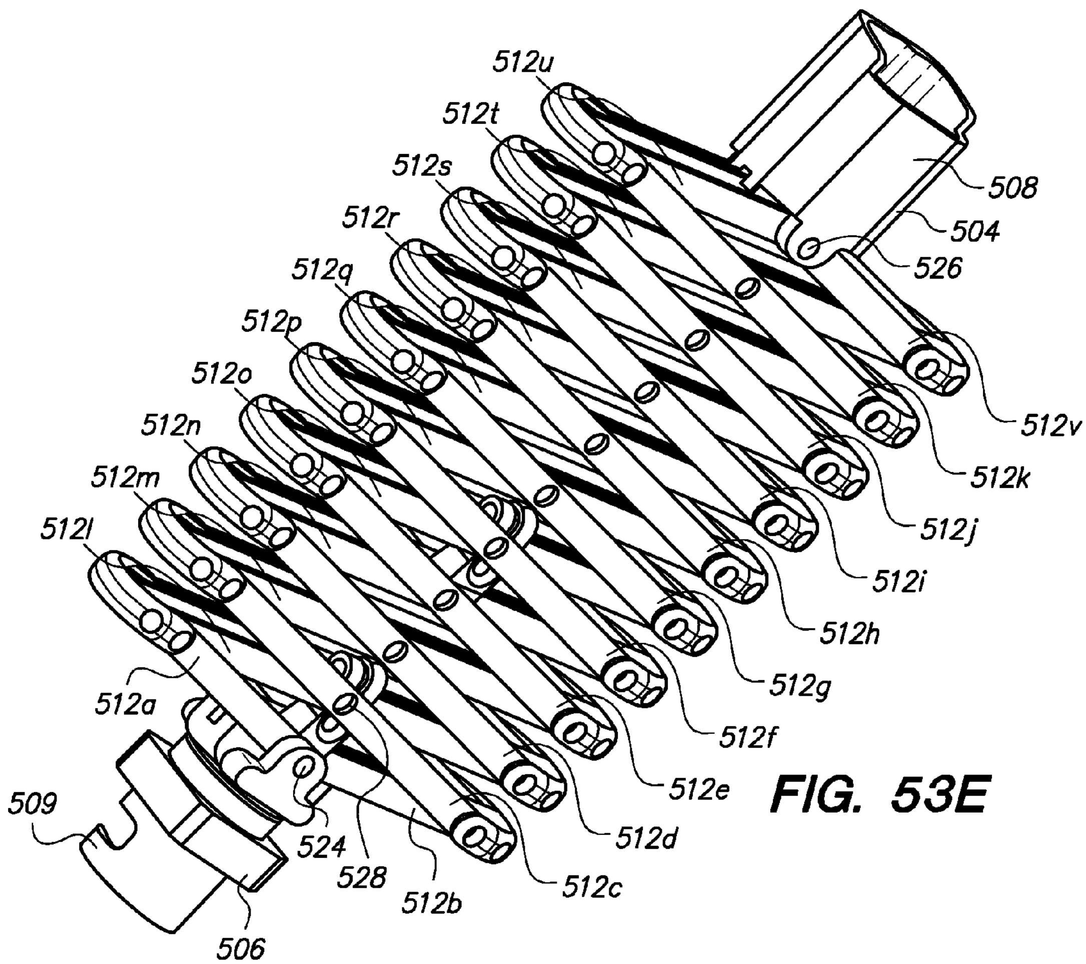

512u
512t
512s
512r
512q
512p
512o
512n
512m
512l
512a
509
524
528
512b
506
512c
512d
512e
512f
512g
512h
512i
512j
512k
512v
526
504
508

FIG. 53E

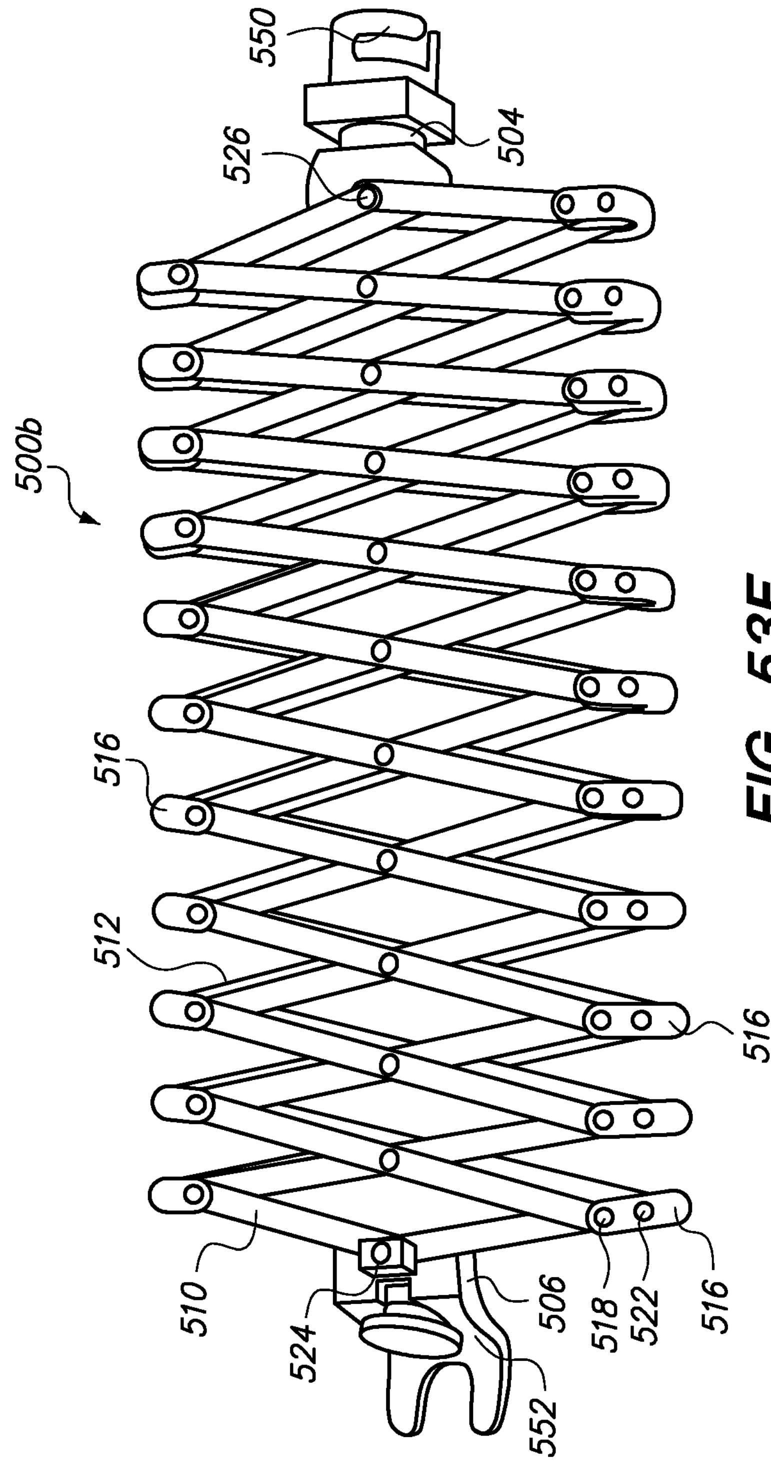


FIG. 53F

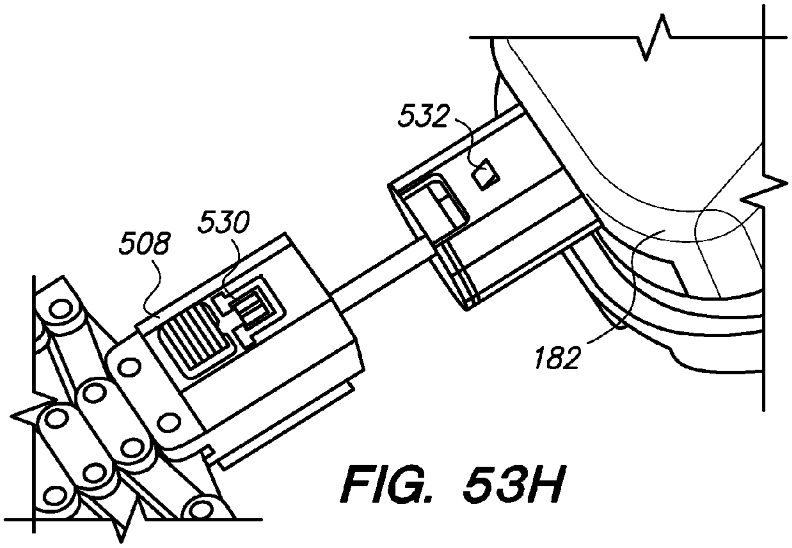


FIG. 53H

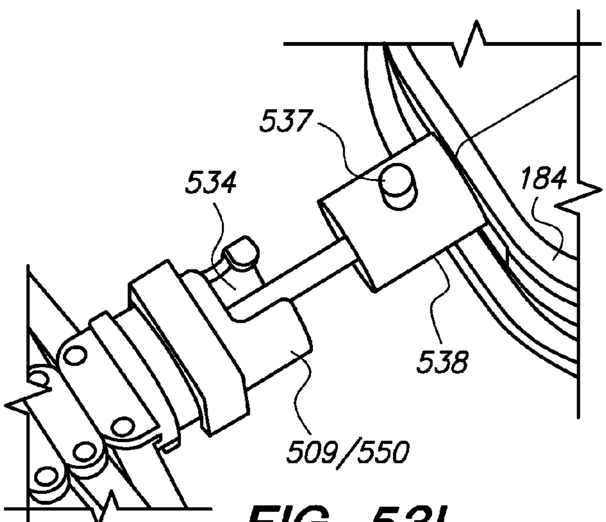


FIG. 53I

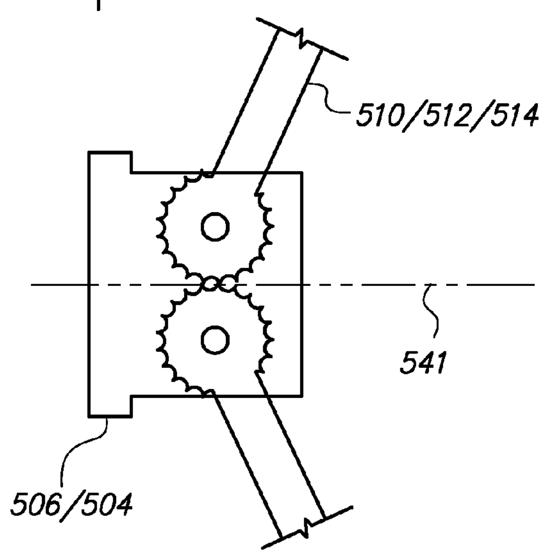
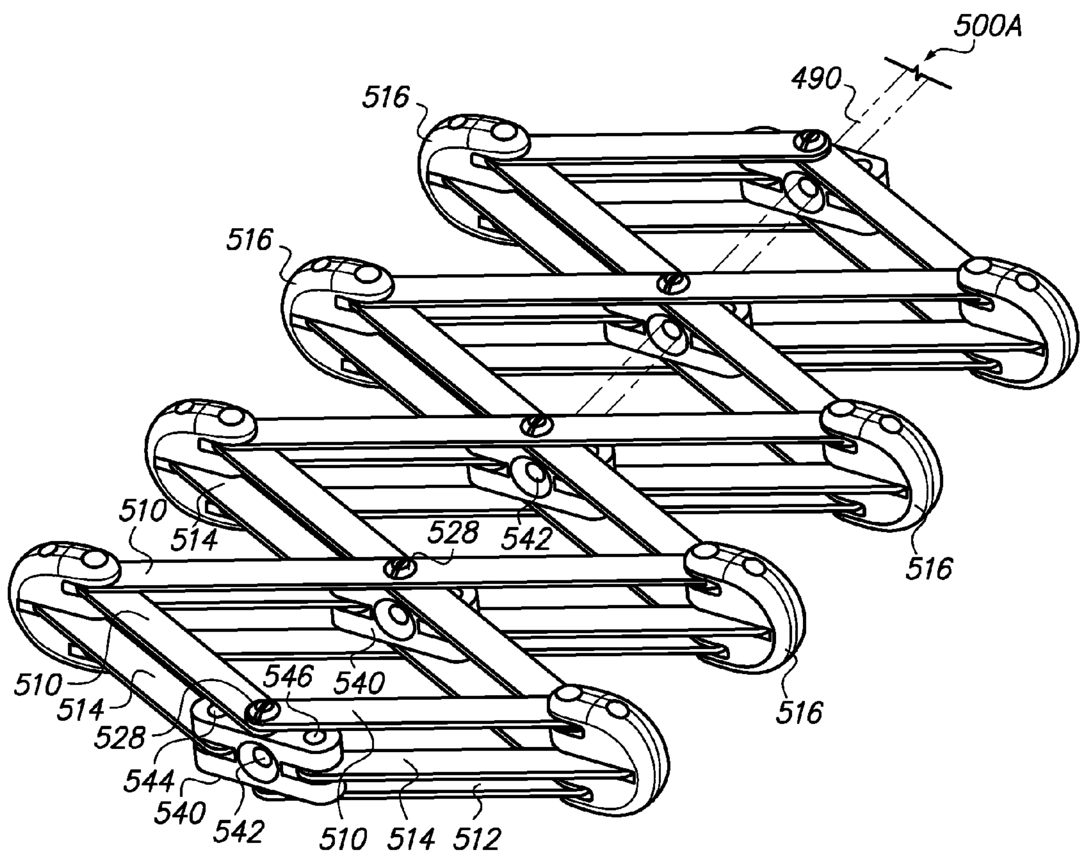


FIG. 53J



500A
490
516
516
510
514
528
542
516
510
514
528
546
540
516
544
540
542
510
514
512

FIG. 53K

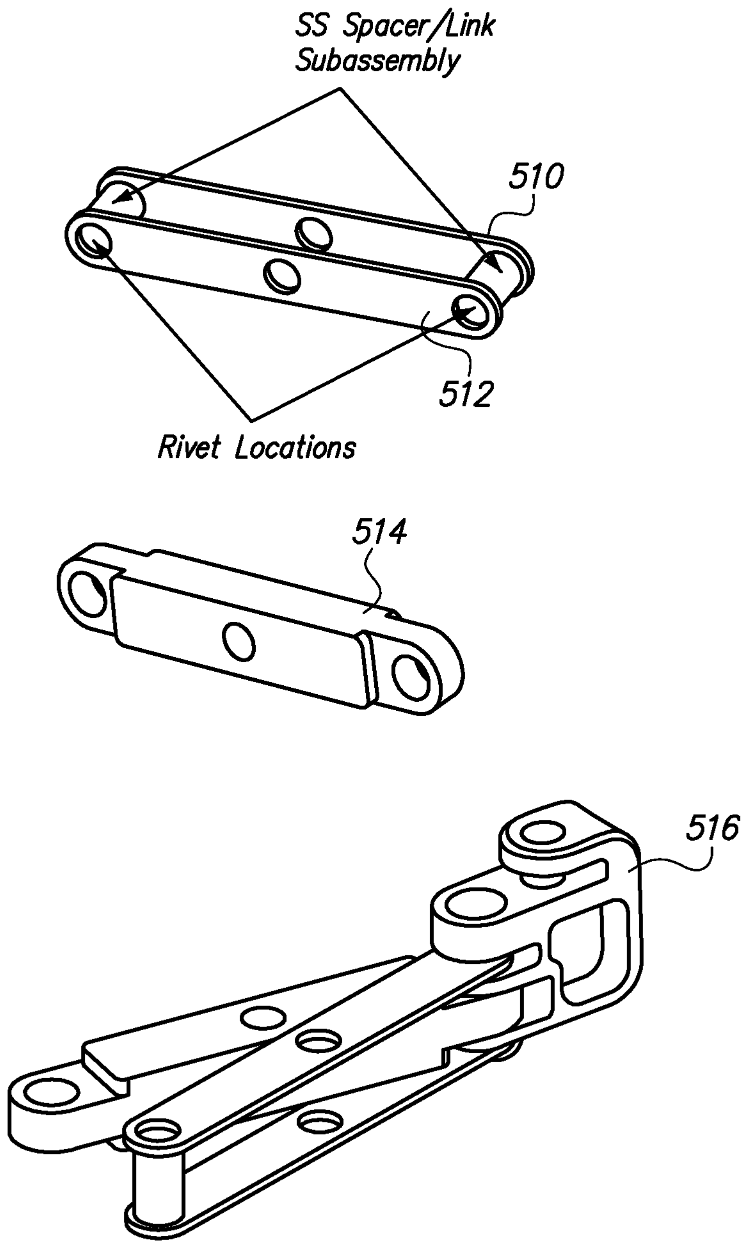


FIG. 53L

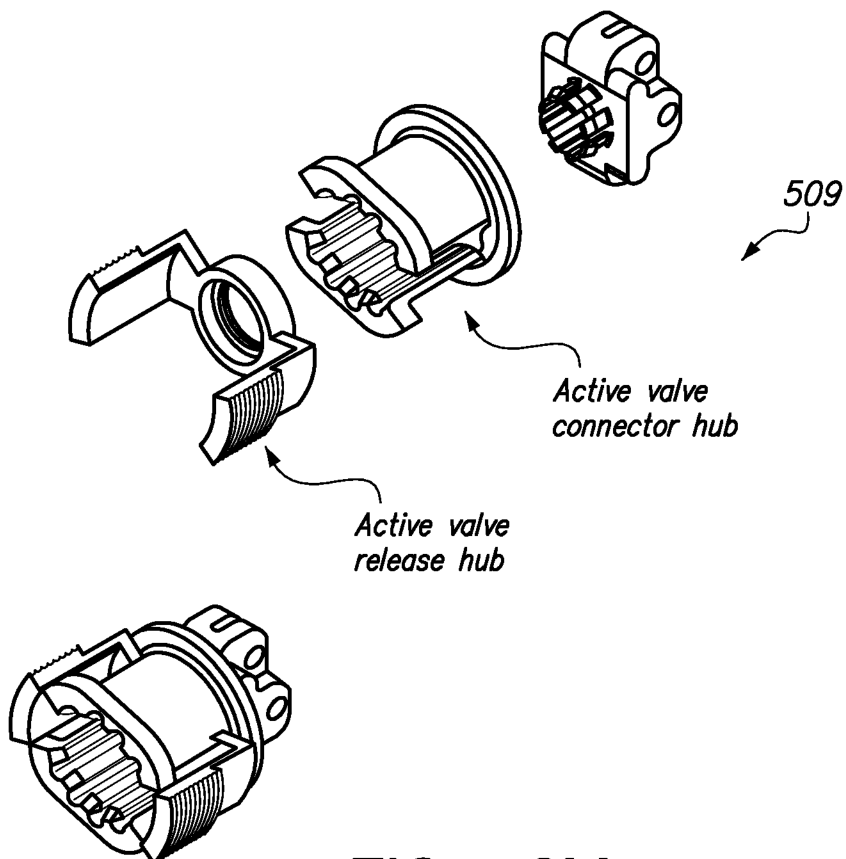


FIG. 53M

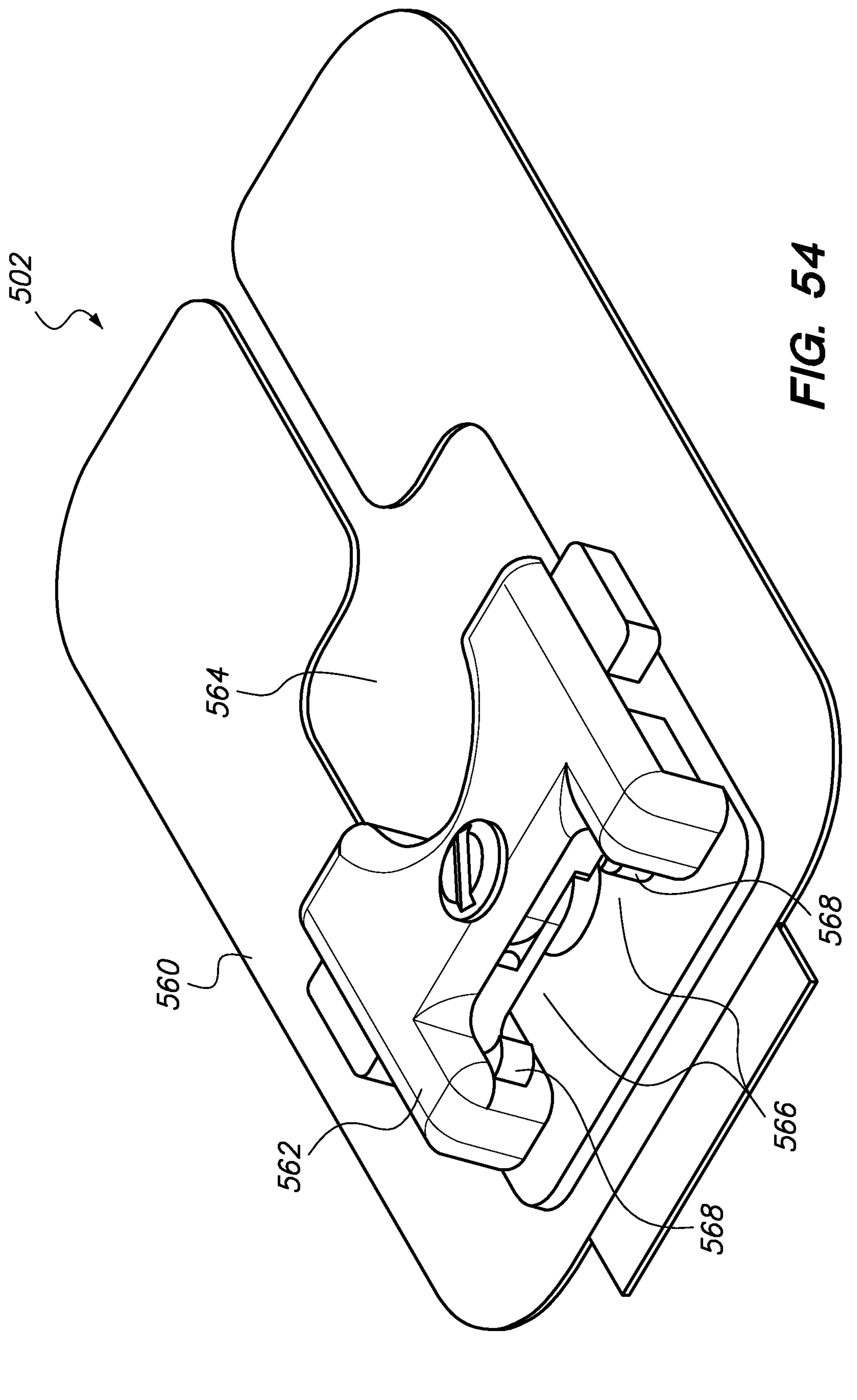


FIG. 54

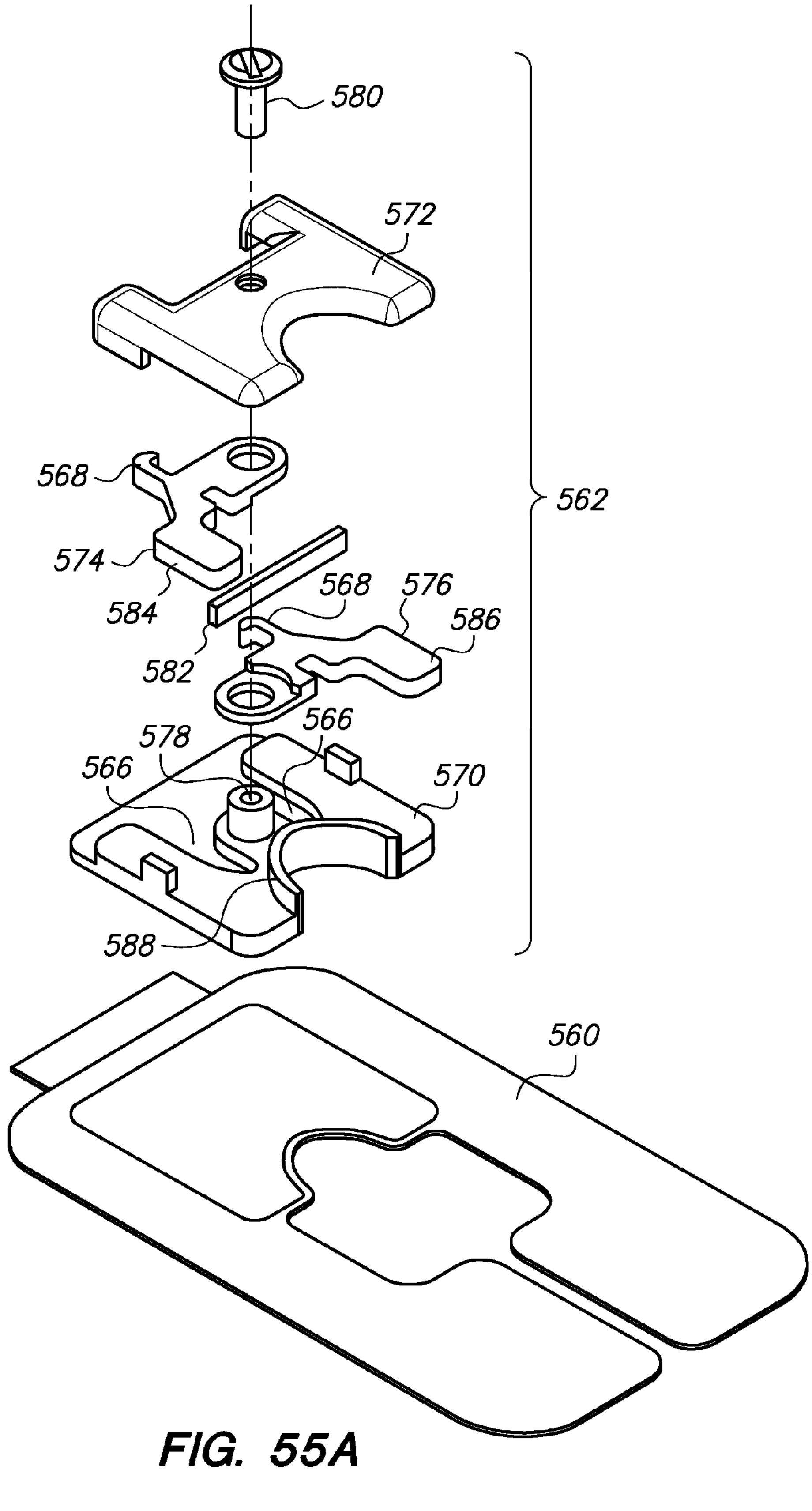


FIG. 55A

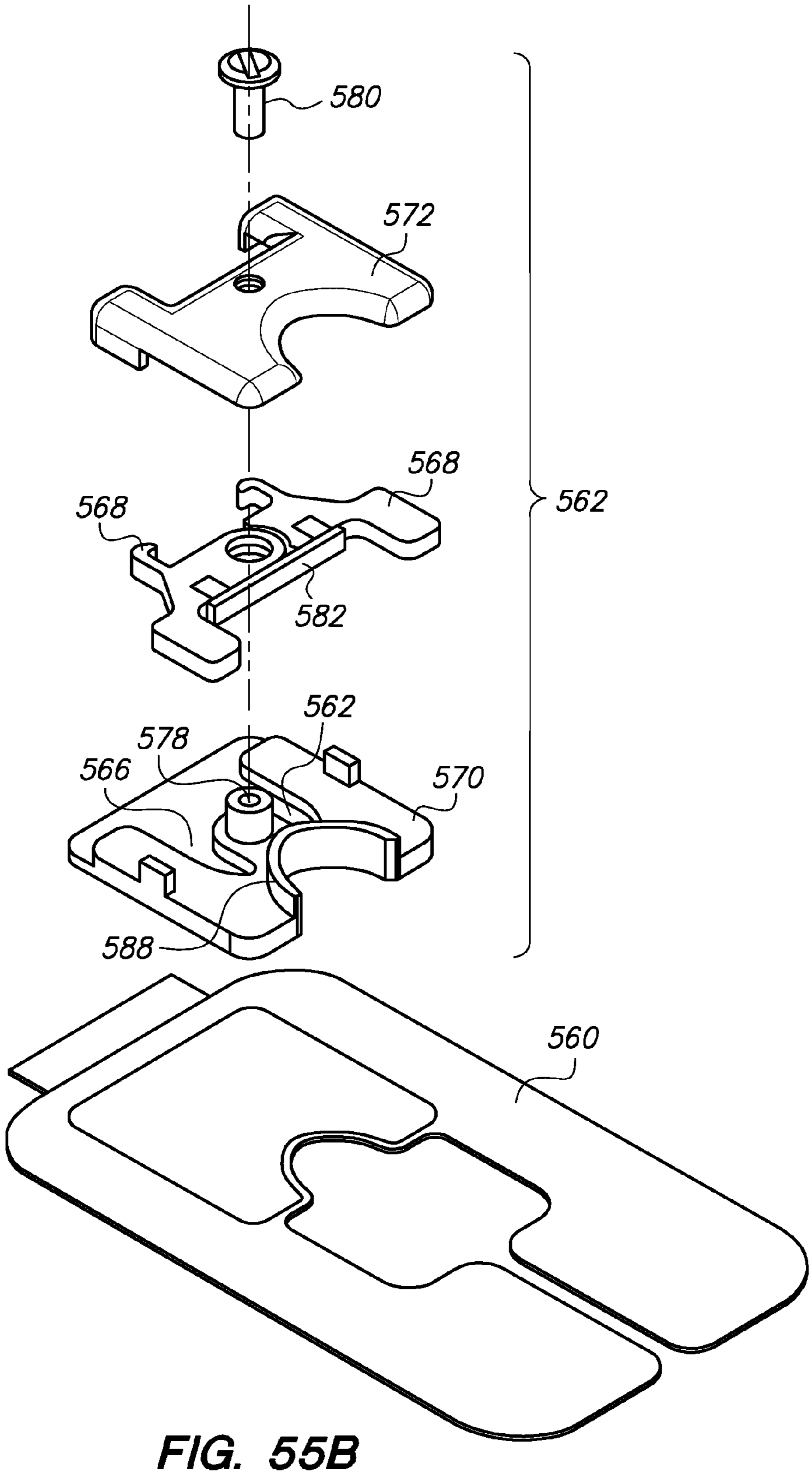


FIG. 55B

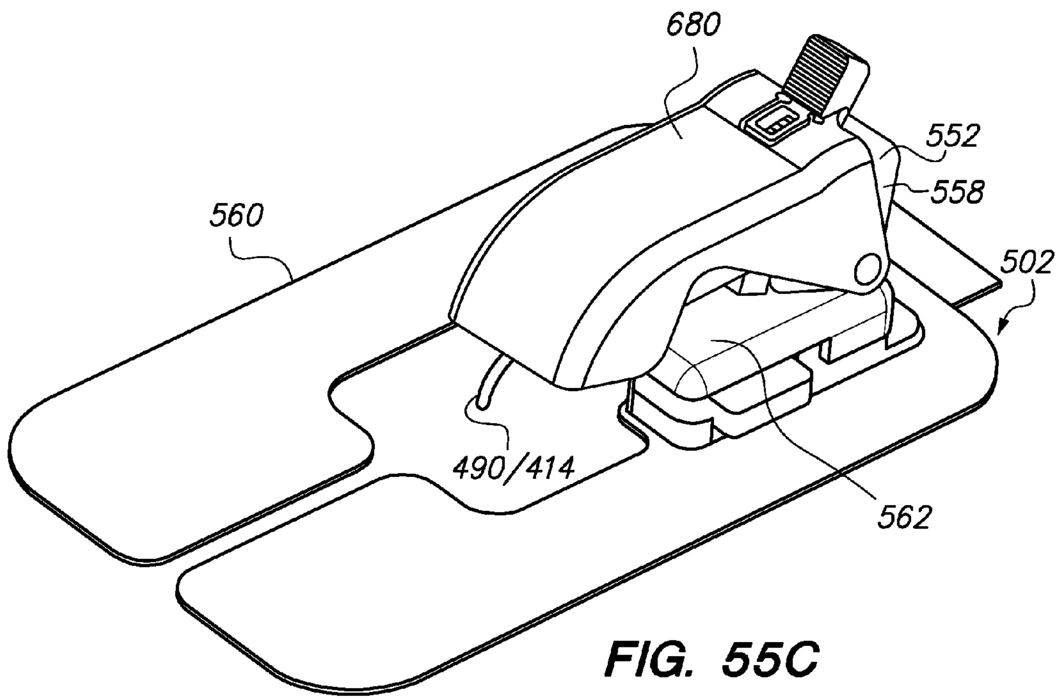


FIG. 55C

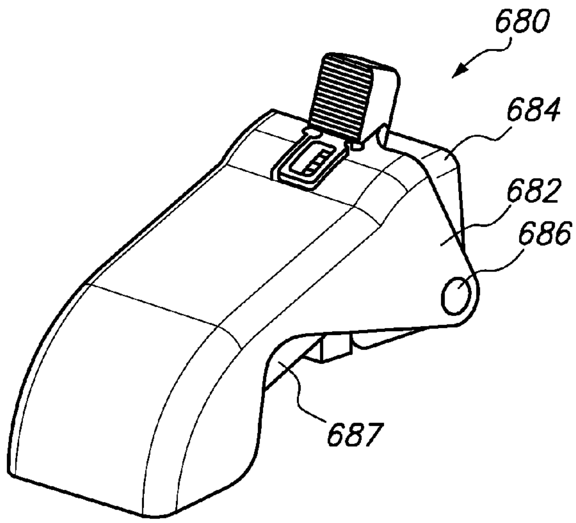


FIG. 55D

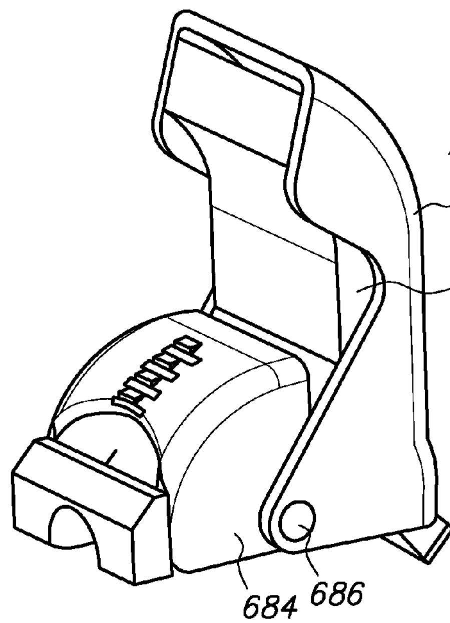


FIG. 55E

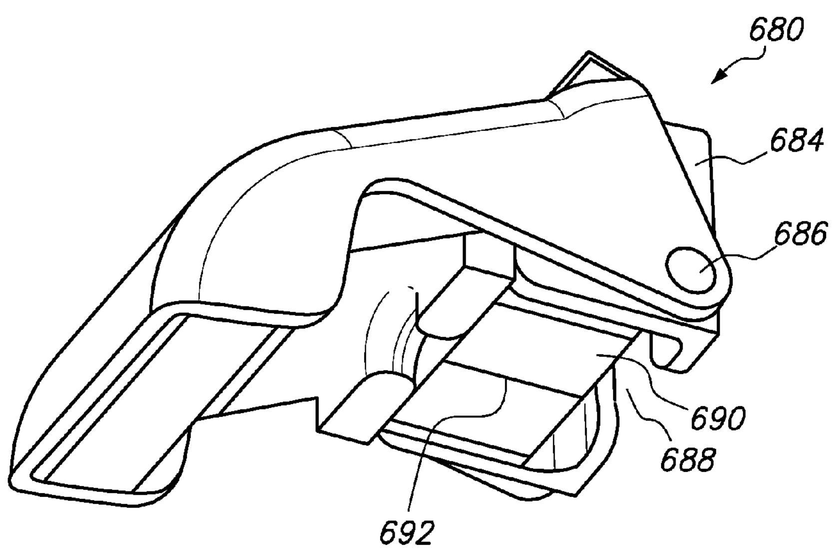


FIG. 55F

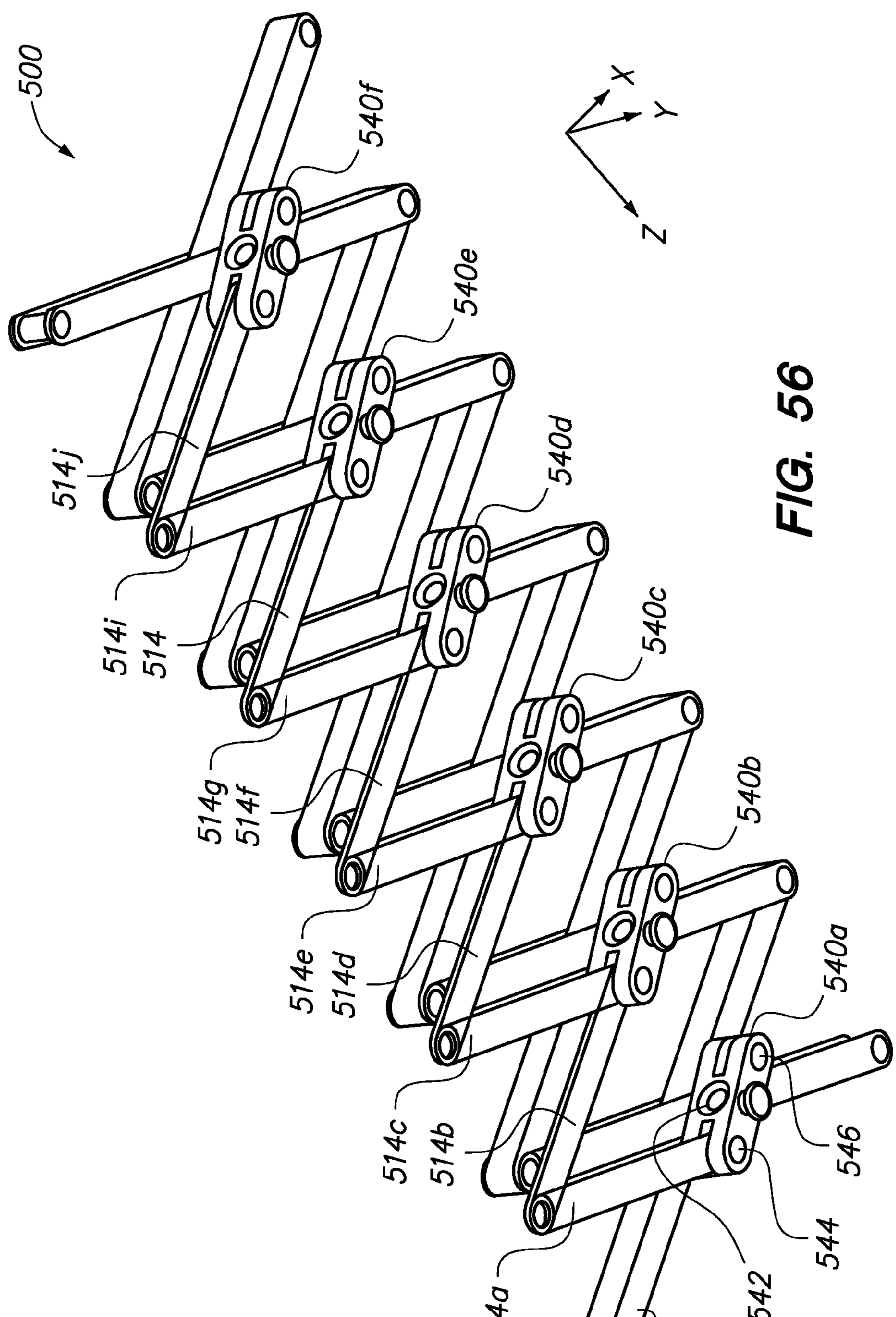

500
540f
540e
540d
540c
540b
540a
X
Y
Z
514j
514i
514
514g
514f
514e
514d
514c
514b
514a
512
542
544
546

FIG. 56

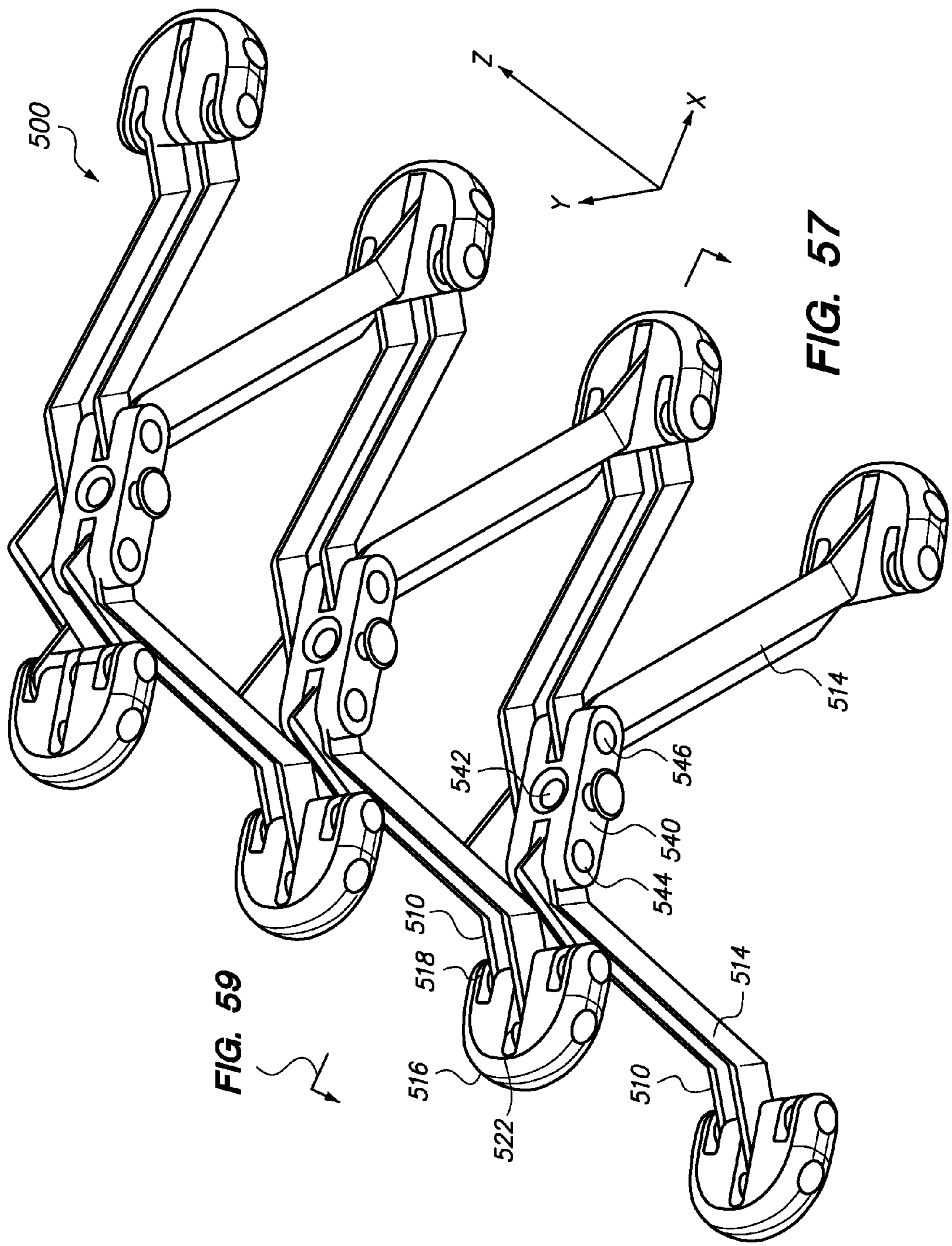


FIG. 57

FIG. 59

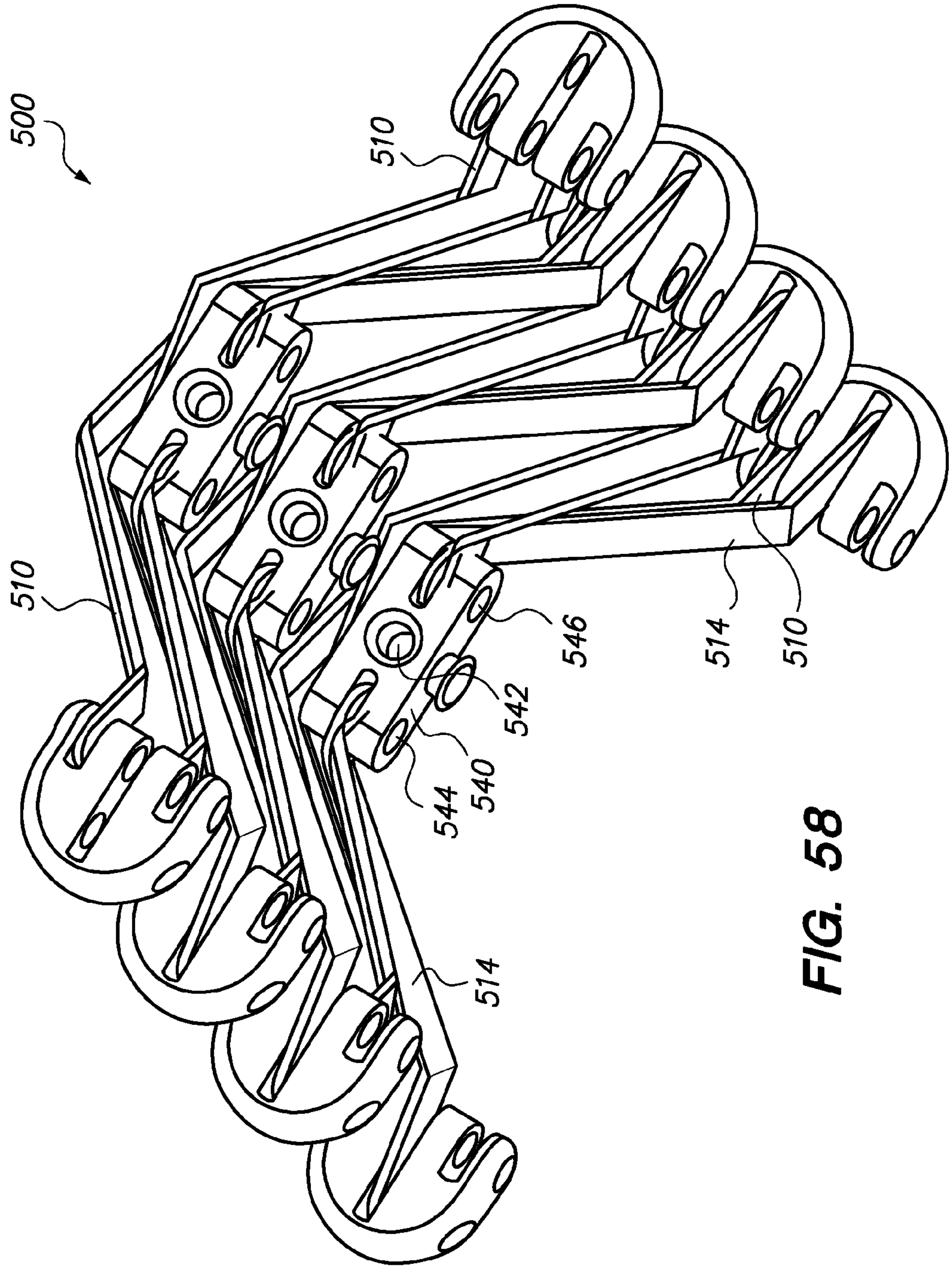


FIG. 58

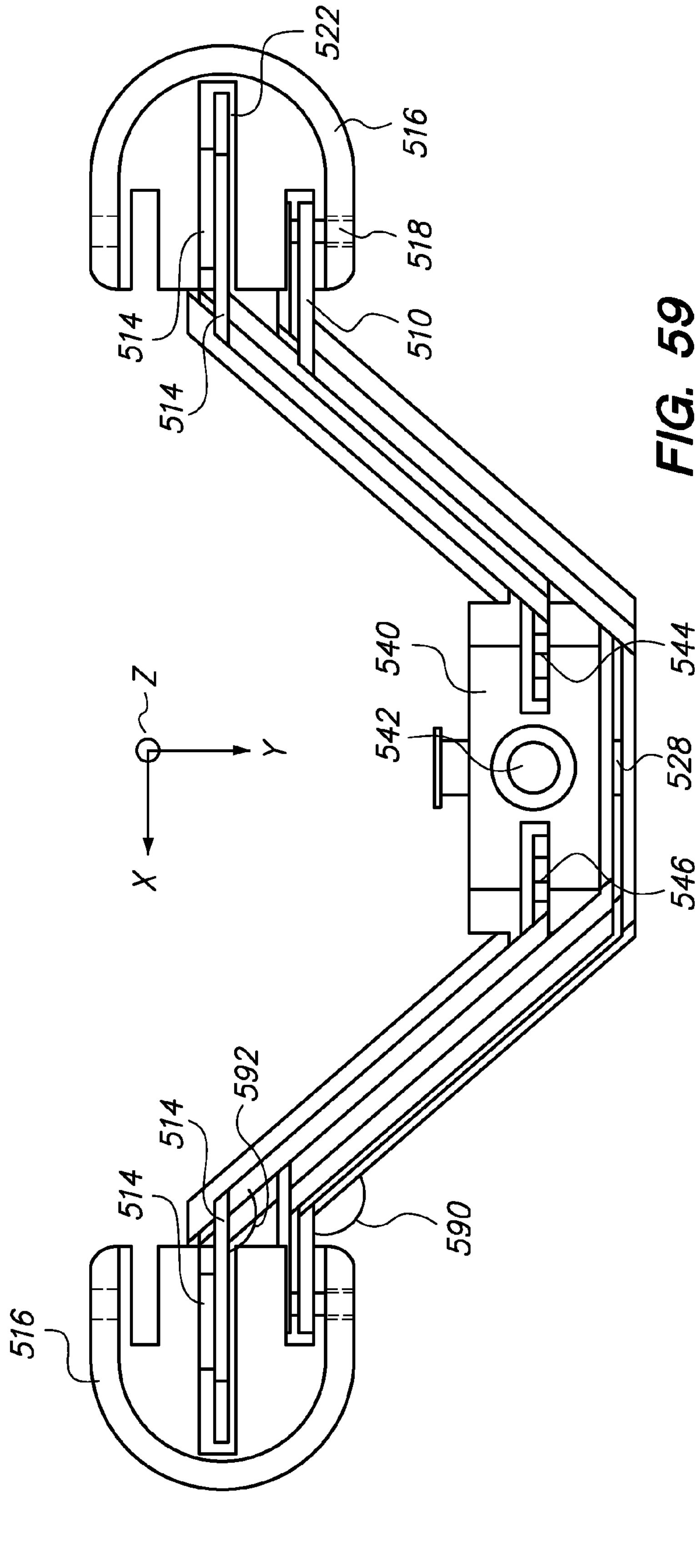

522
516
518
510
514
514
540
544
542
528
546
Z
Y
X
592
514
514
590
516

FIG. 59

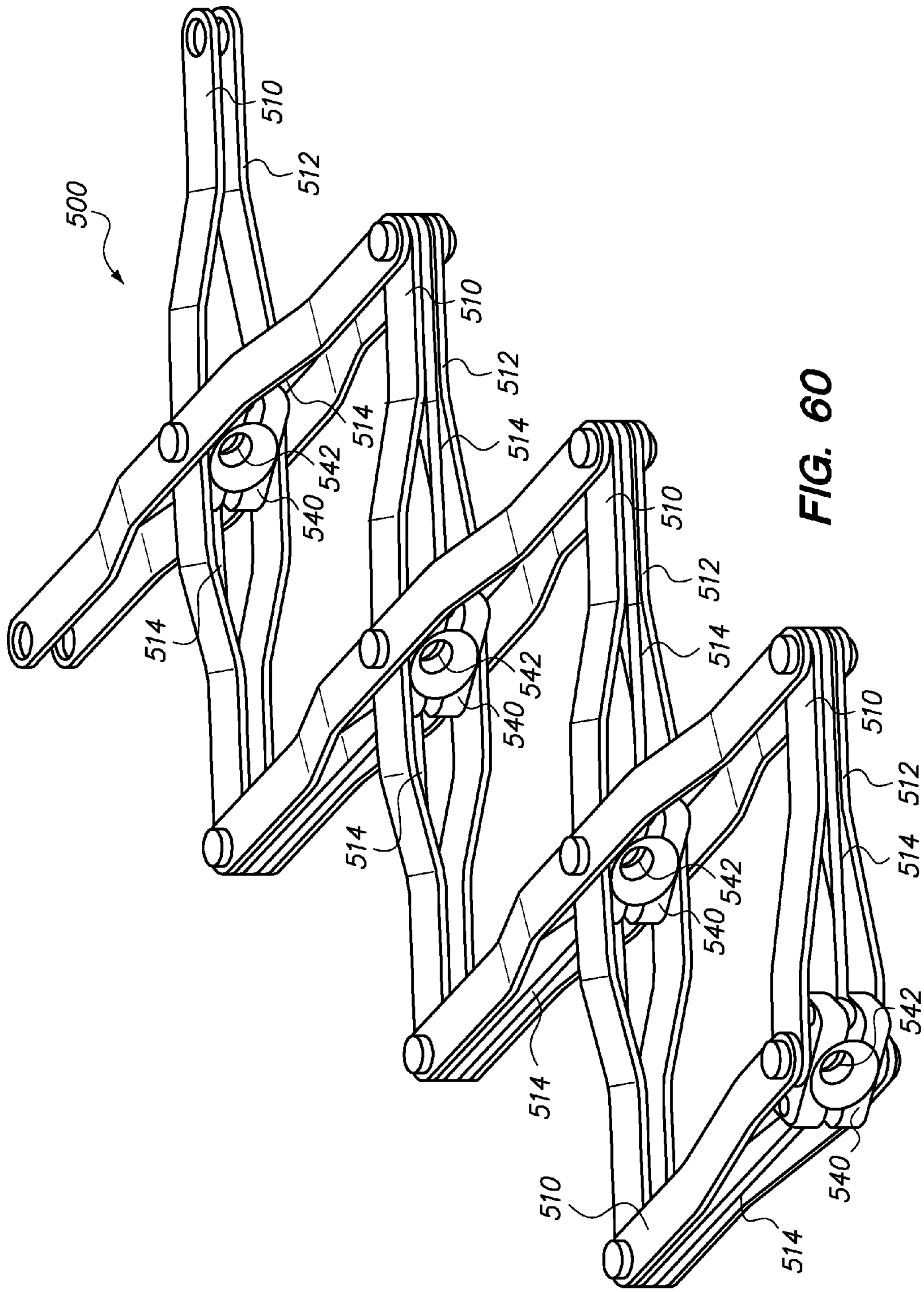


FIG. 60

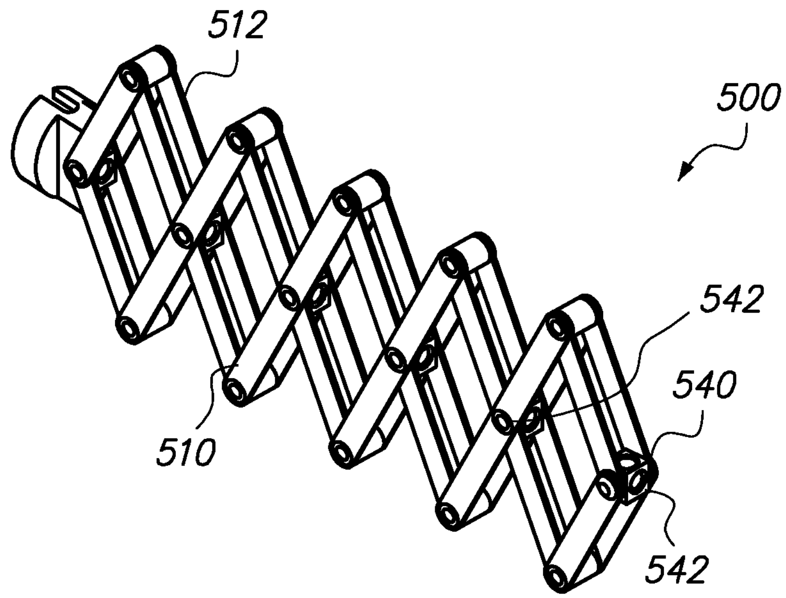


FIG. 61A

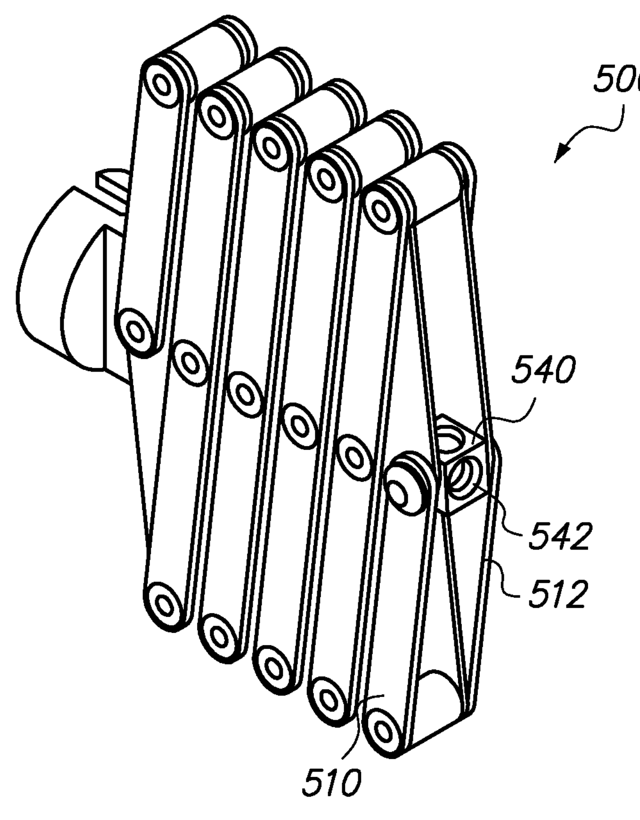


FIG. 61B

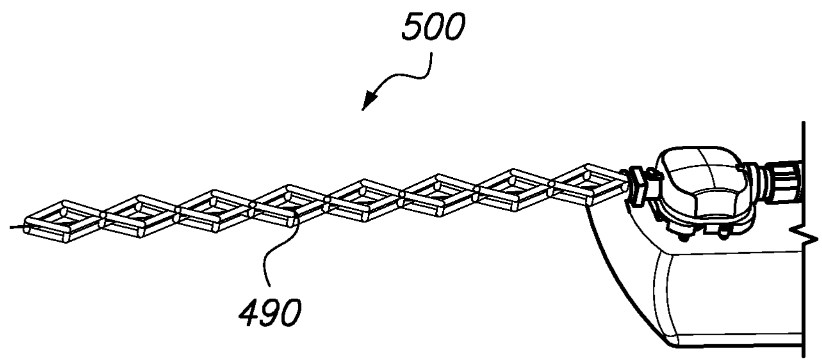


FIG. 61C

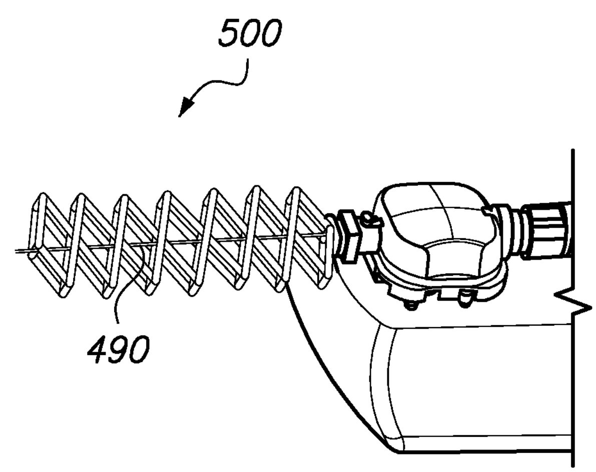


FIG. 61D

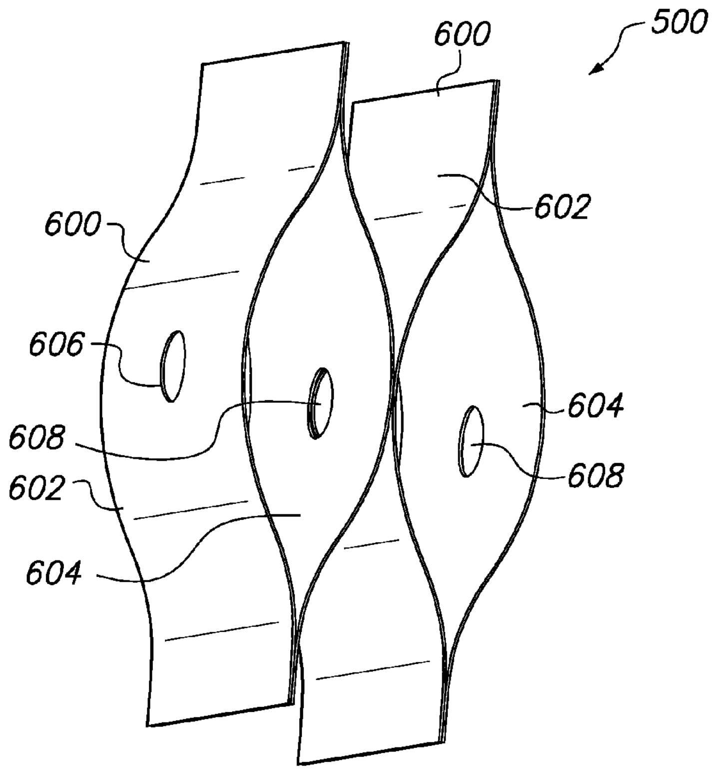


FIG. 62

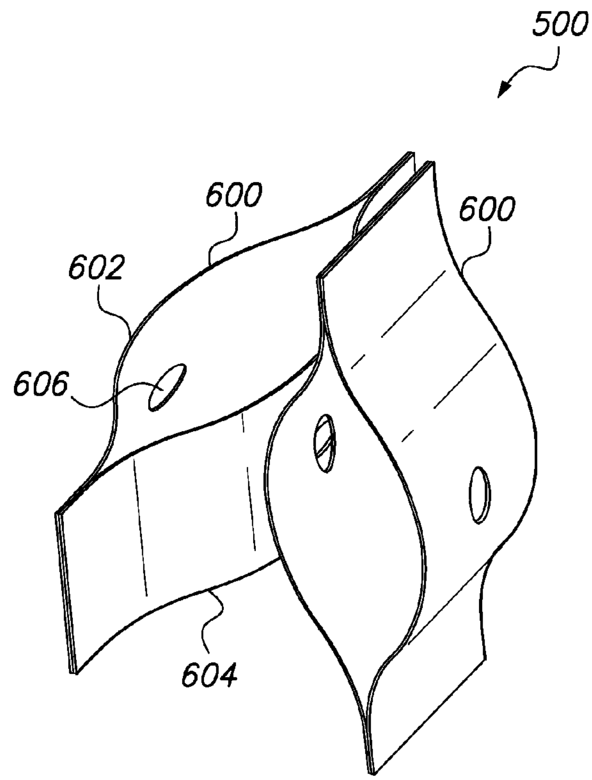


FIG. 63

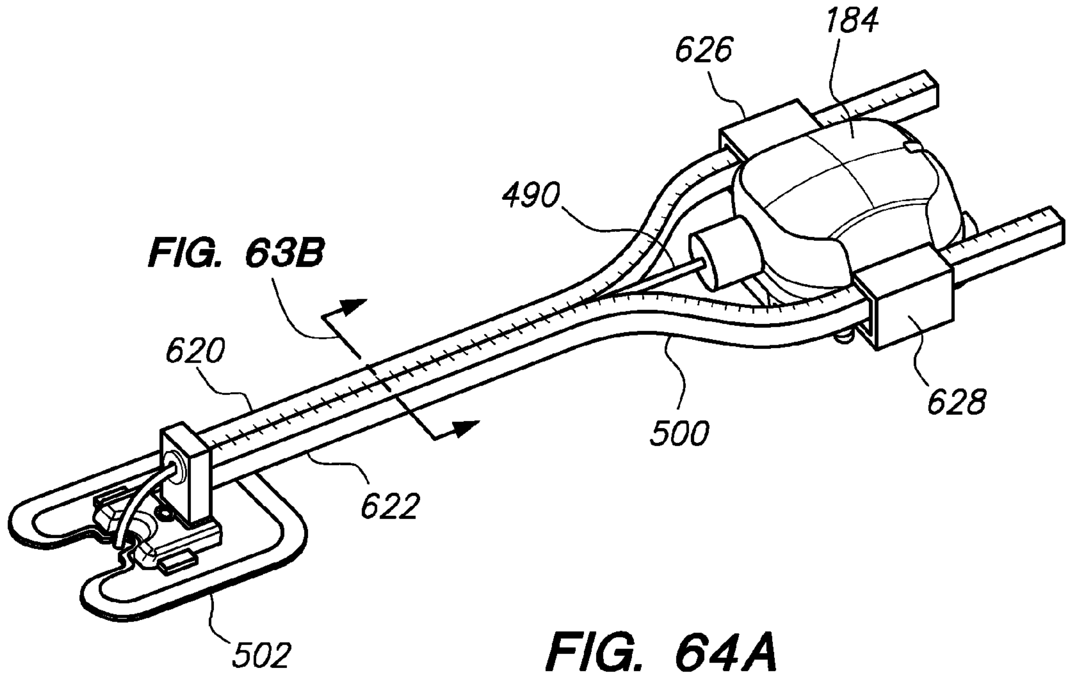


FIG. 64A

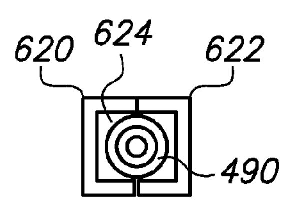


FIG. 64B

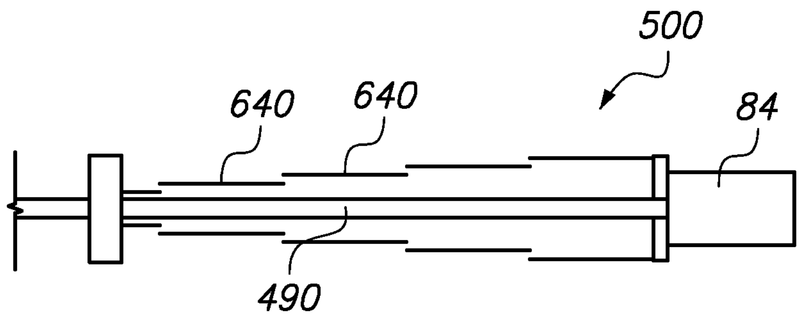


FIG. 65A

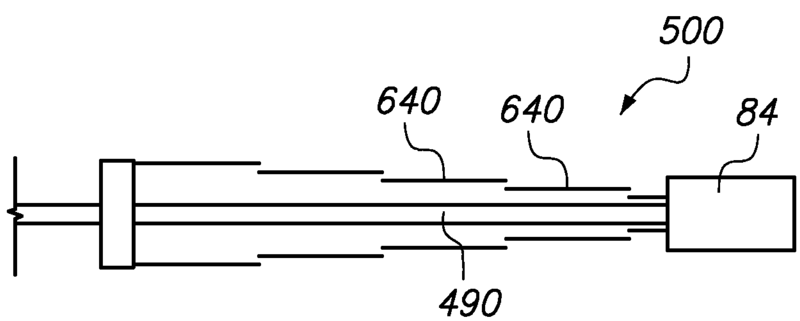


FIG. 65B

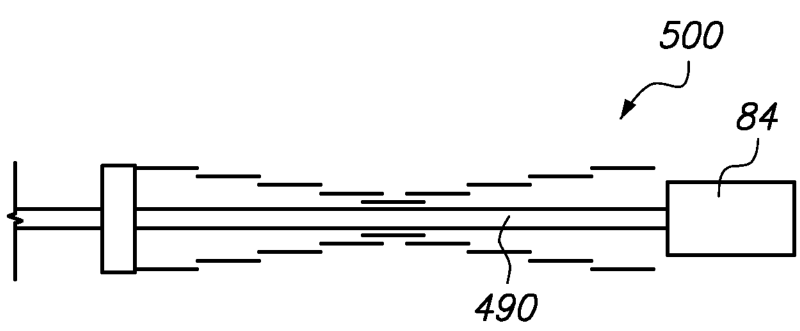


FIG. 65C

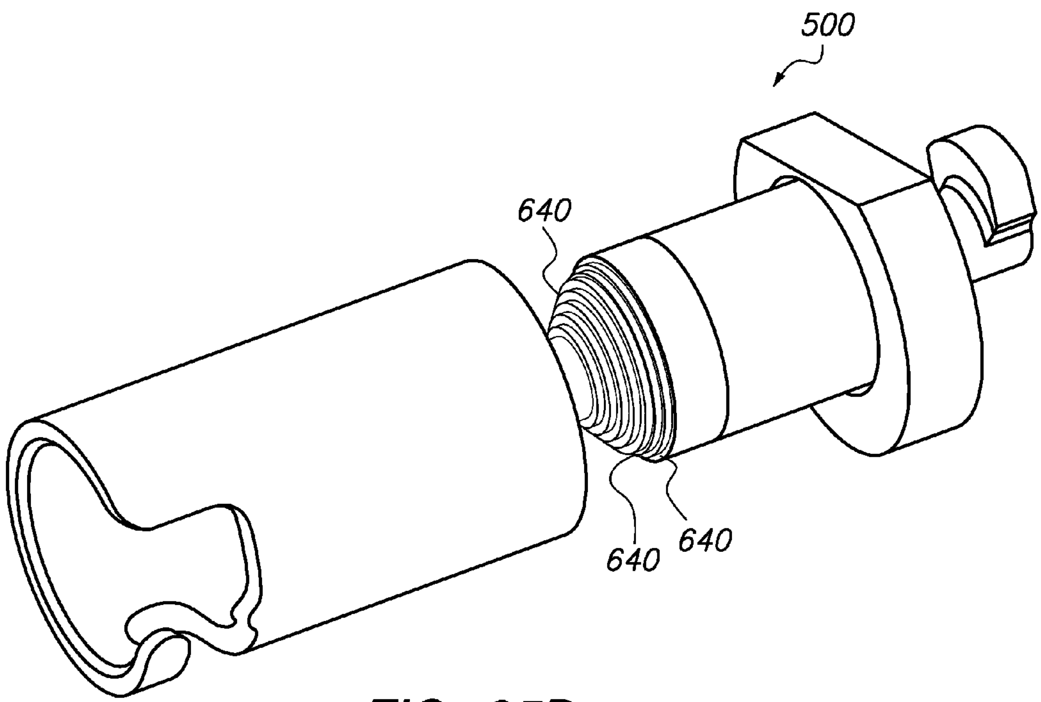


FIG. 65D

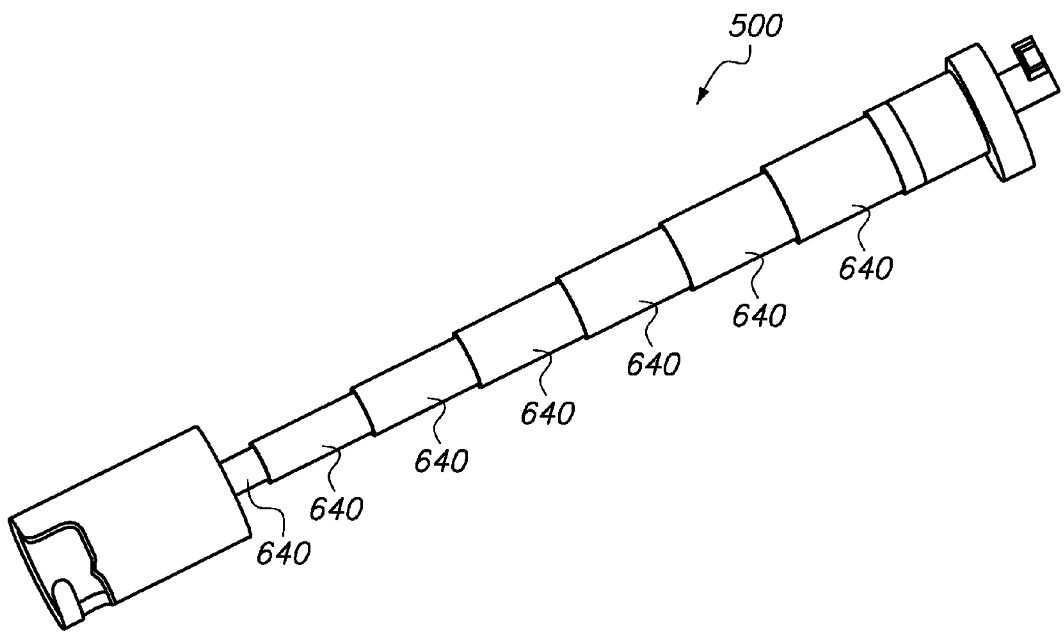


FIG. 65E

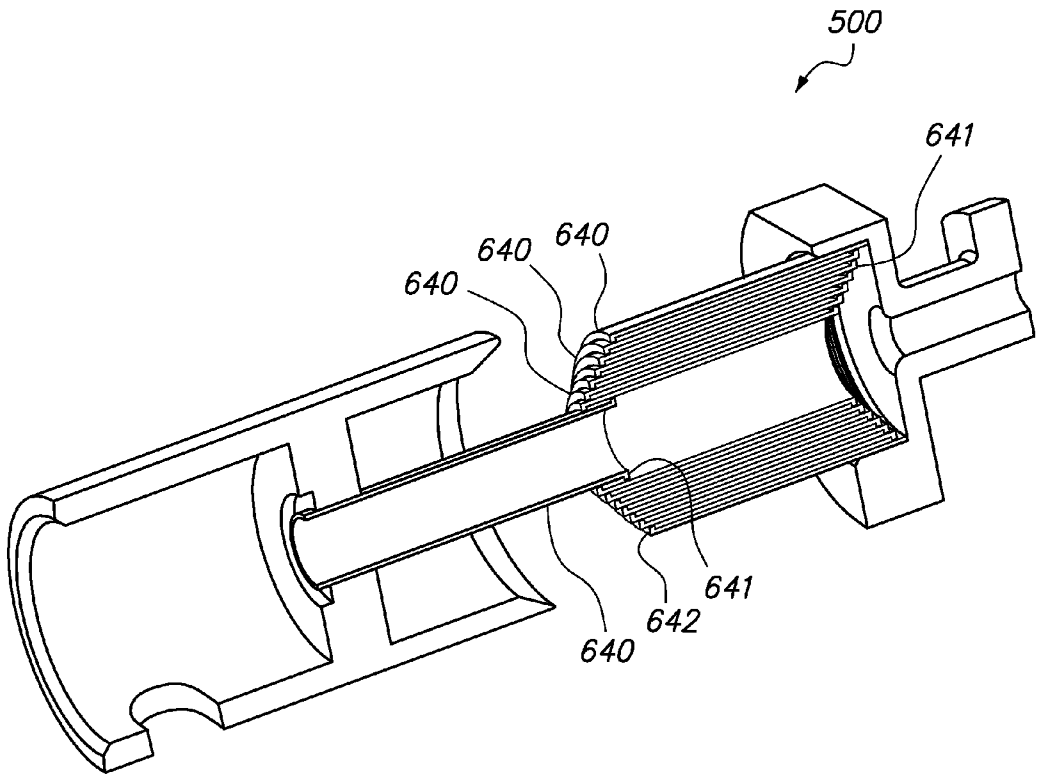


FIG. 65F

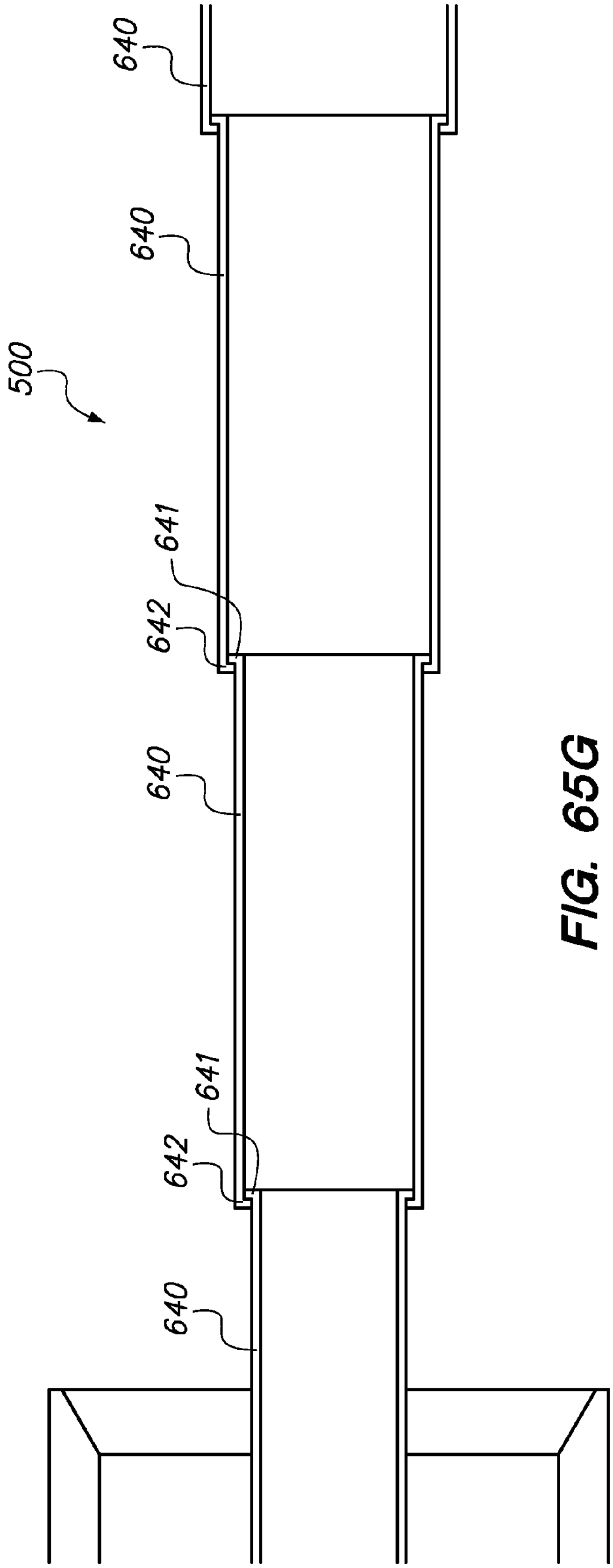


FIG. 65G

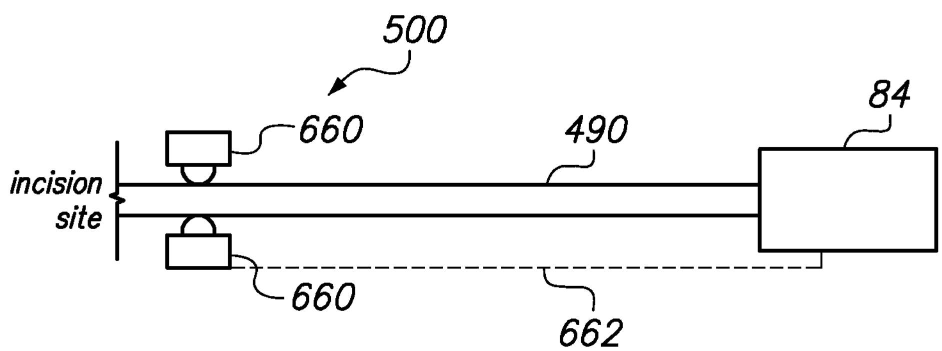


FIG. 66A

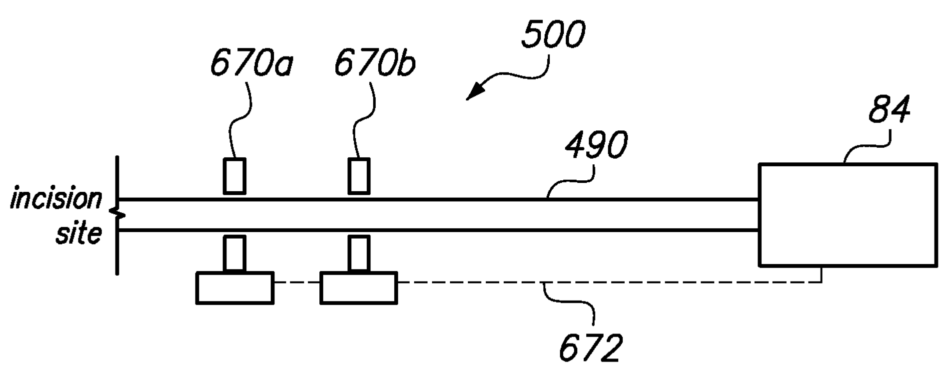


FIG. 66B

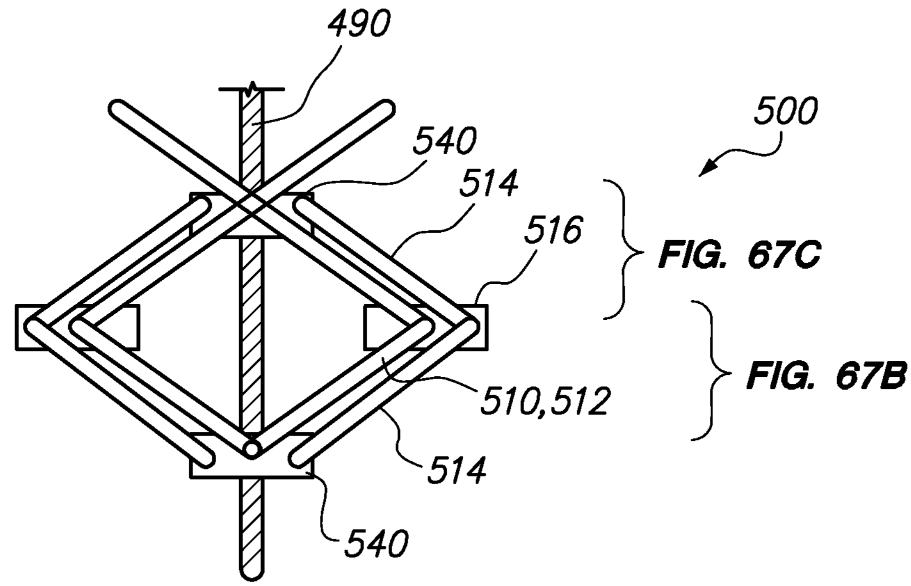


FIG. 67A

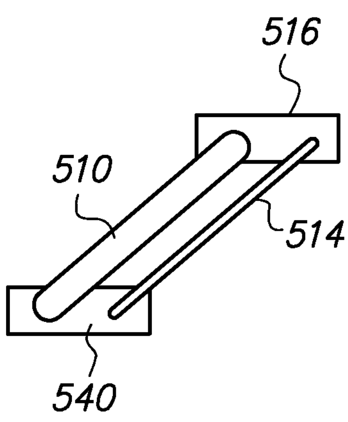


FIG. 67B

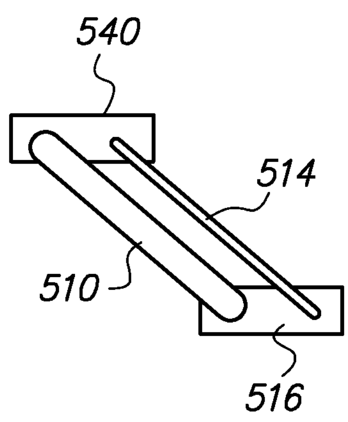


FIG. 67C

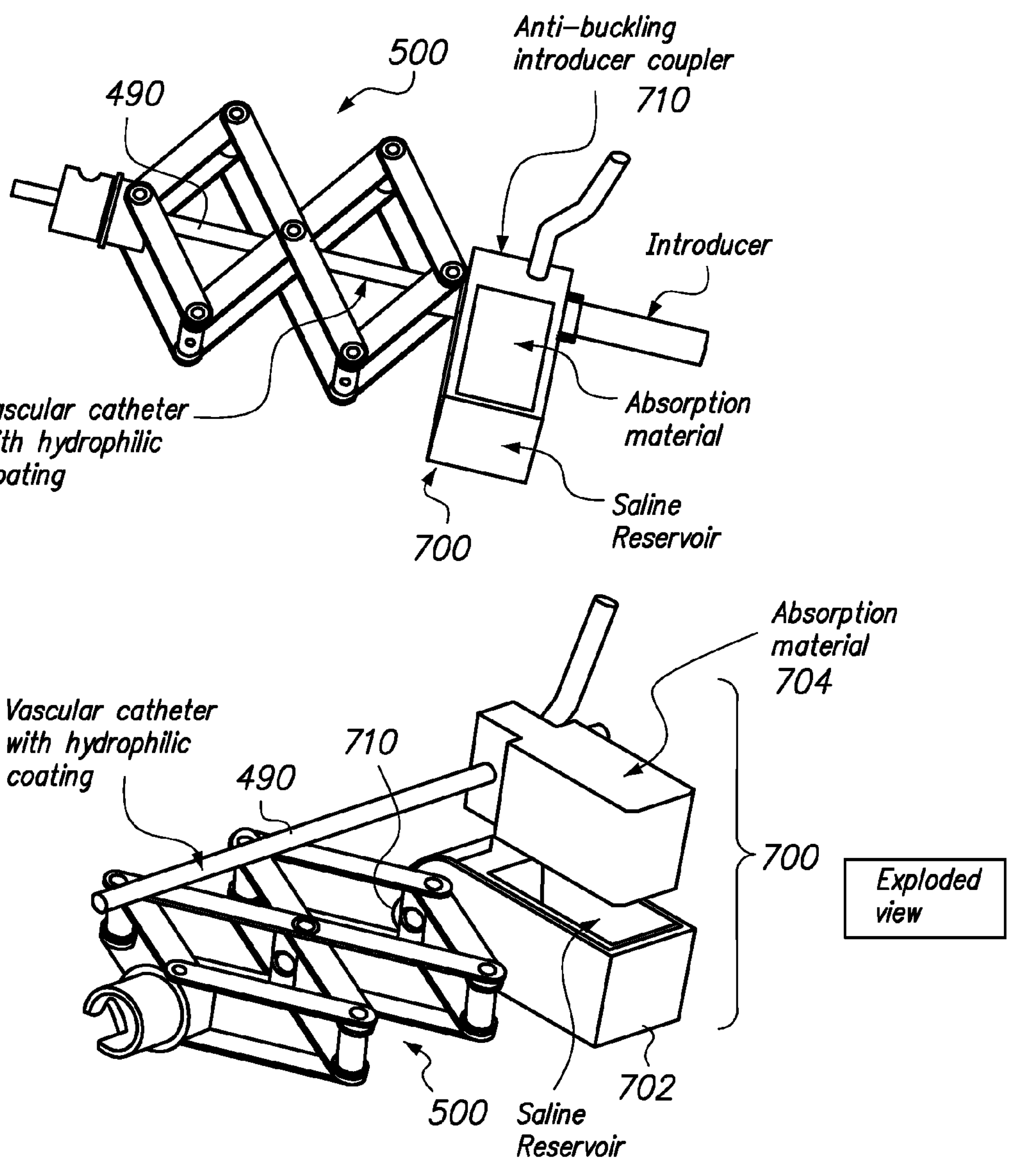

500
490
Anti-buckling introducer coupler
710
Introducer
Vascular catheter with hydrophilic coating
Absorption material
Saline Reservoir
700
Absorption material
704
Vascular catheter with hydrophilic coating
710
490
700
Exploded view
500
Saline Reservoir
702

FIG. 68

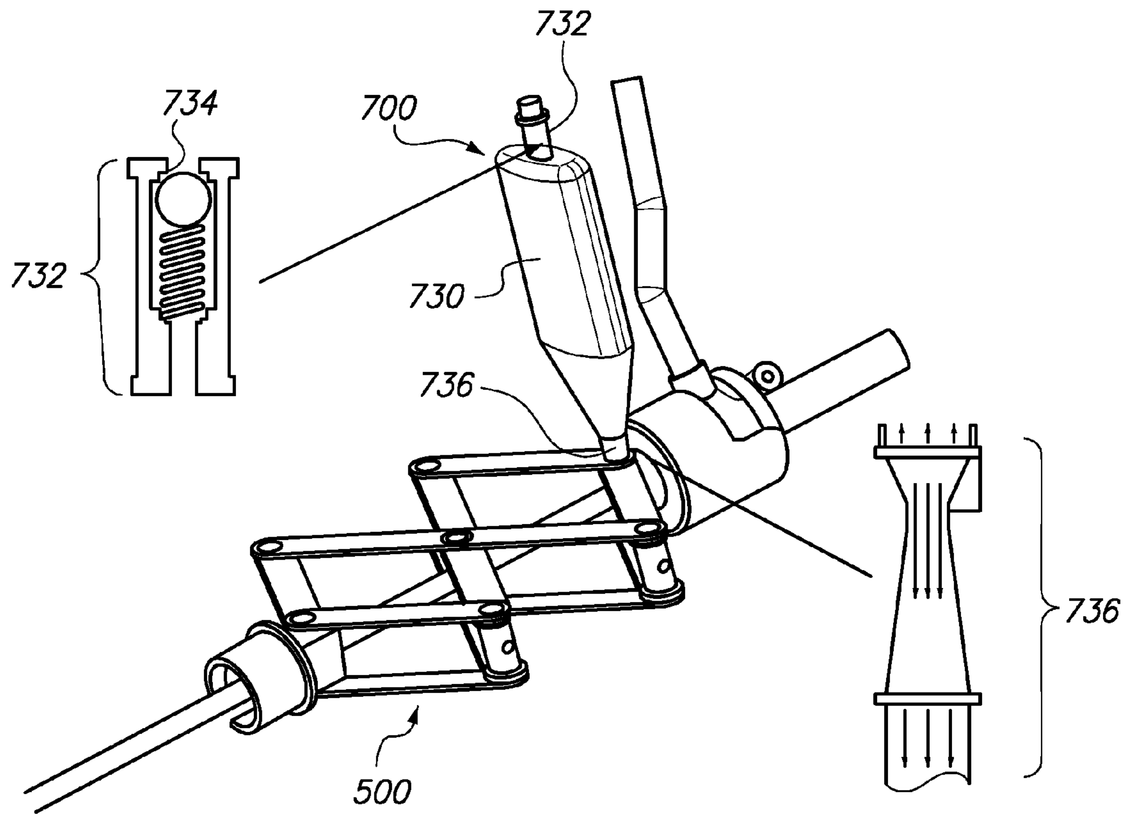


FIG. 69

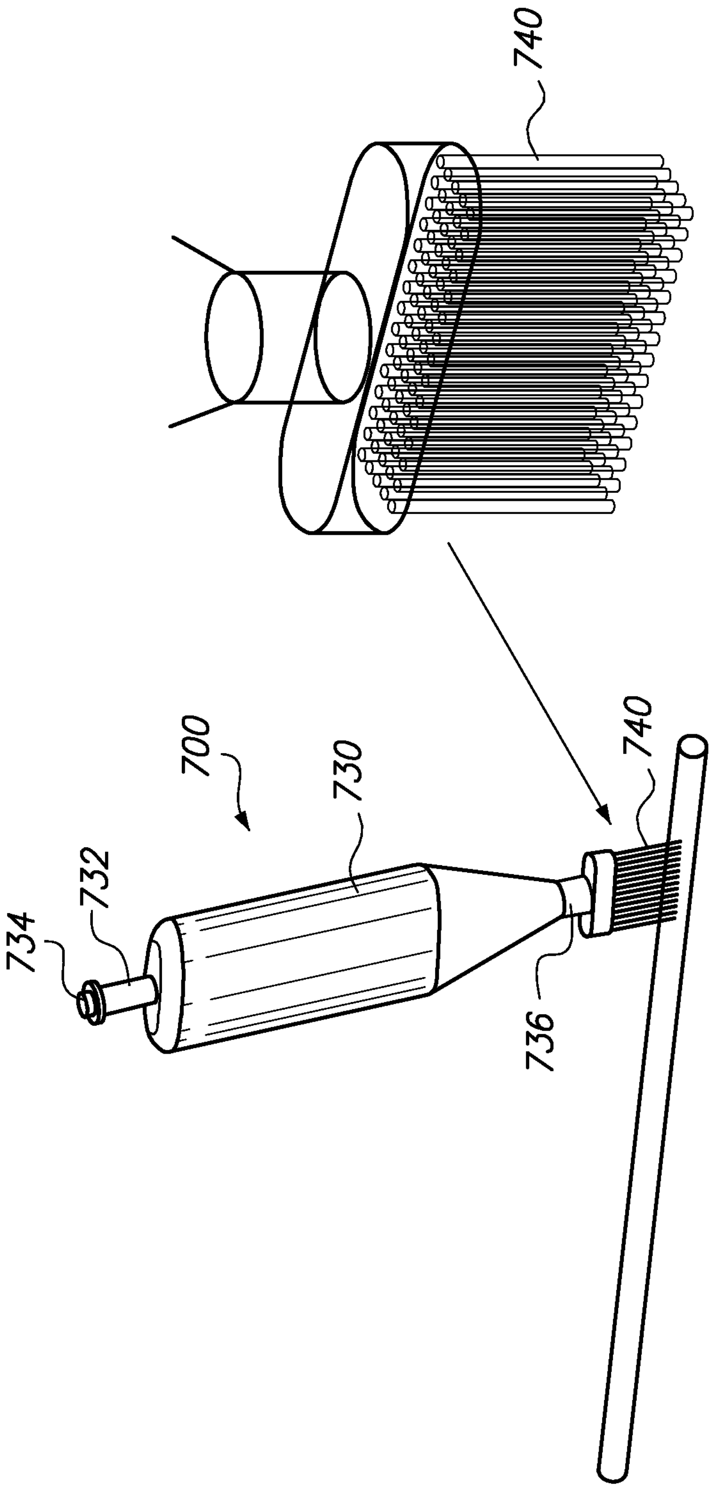


FIG. 70

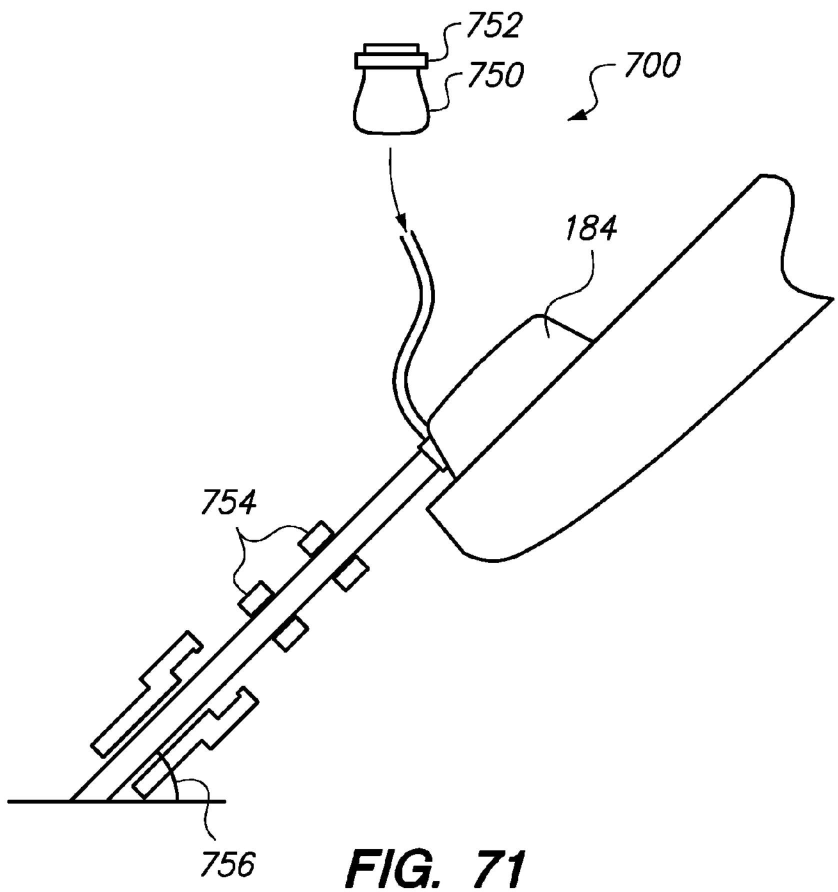

752
750
700
184
754
756

FIG. 71

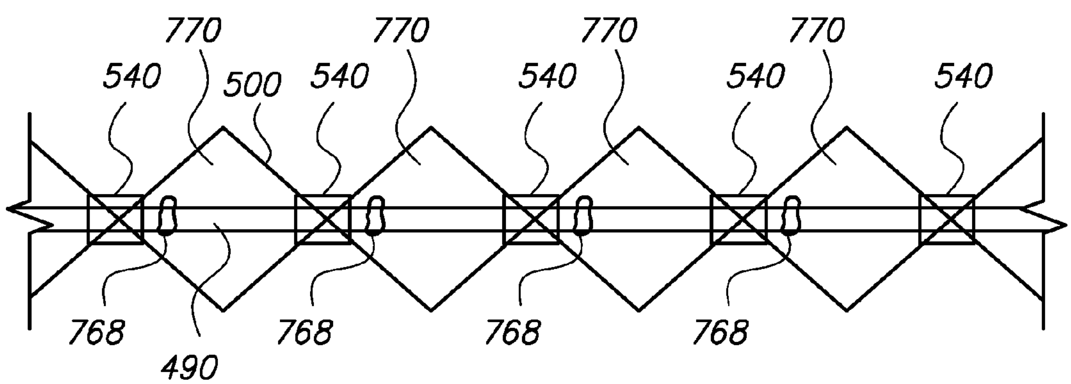

770
770
770
770
540
500
540
540
540
540
768
490
768
768
768

FIG. 72

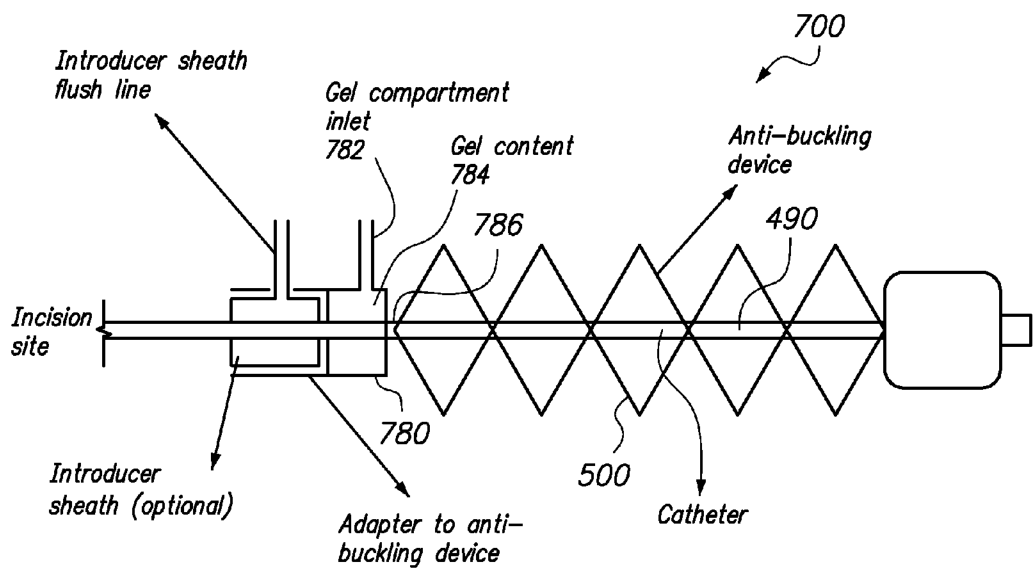

700
Introducer sheath flush line
Gel compartment inlet 782
Gel content 784
786
Anti–buckling device
490
Incision site
780
500
Introducer sheath (optional)
Adapter to anti–buckling device
Catheter

FIG. 73

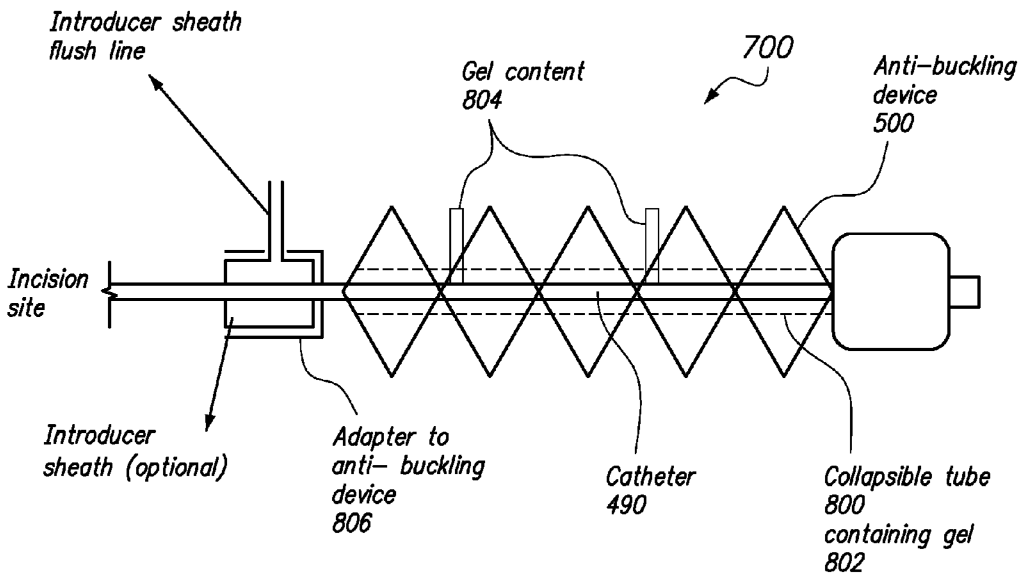

Introducer sheath flush line
700
Gel content 804
Anti–buckling device 500
Incision site
Introducer sheath (optional)
Adapter to anti– buckling device 806
Catheter 490
Collapsible tube 800 containing gel 802

FIG. 74

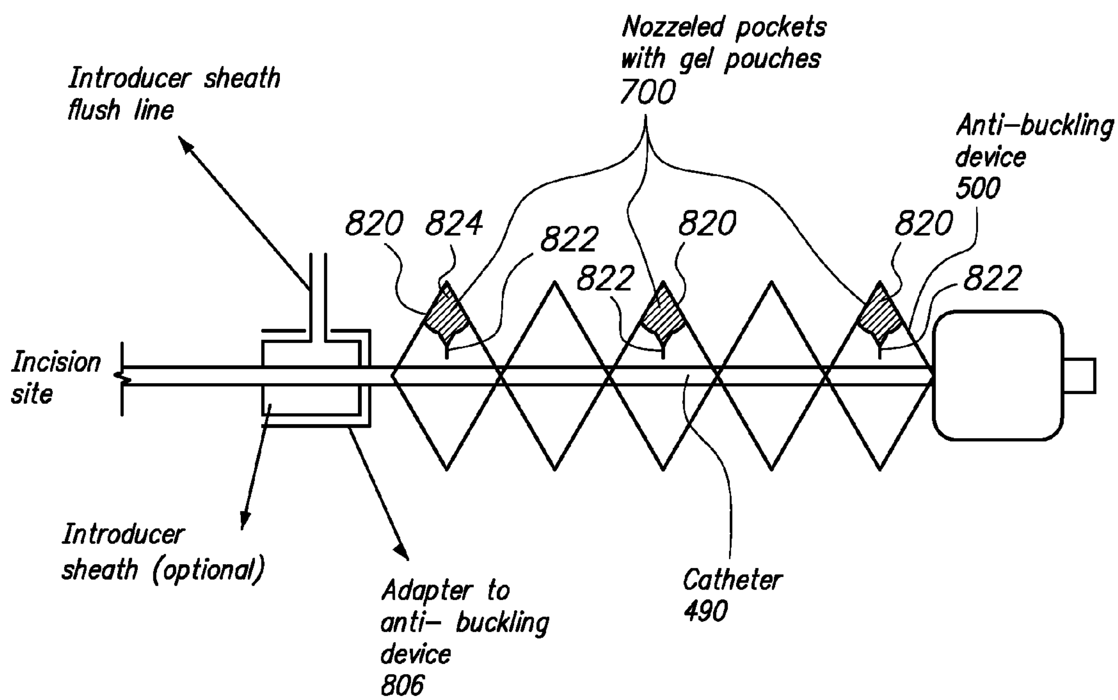

Nozzeled pockets
with gel pouches
700
Introducer sheath
flush line
Anti–buckling
device
500
820
824
822
820
822
820
822
Incision
site
Introducer
sheath (optional)
Adapter to
anti– buckling
device
806
Catheter
490

FIG. 75

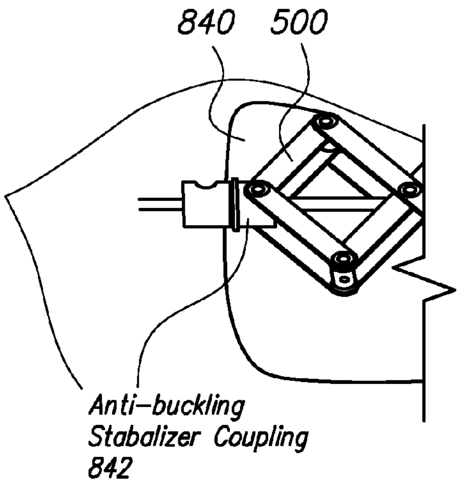


FIG. 76

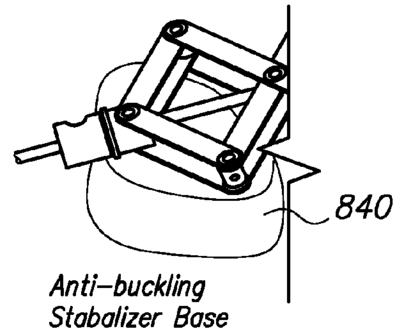


FIG. 77

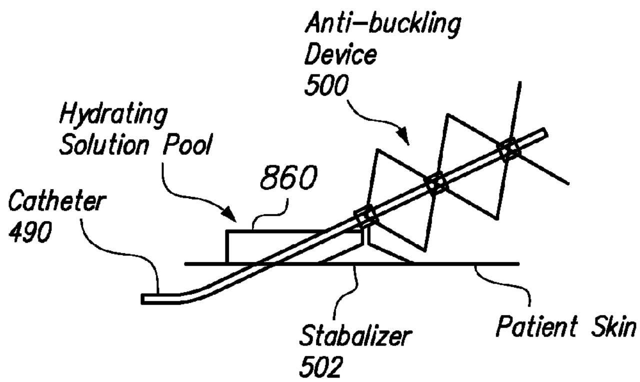


FIG. 78

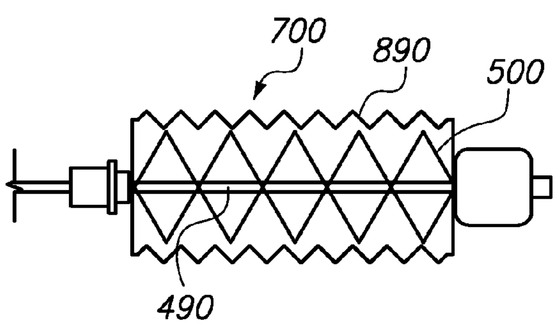


FIG. 78A

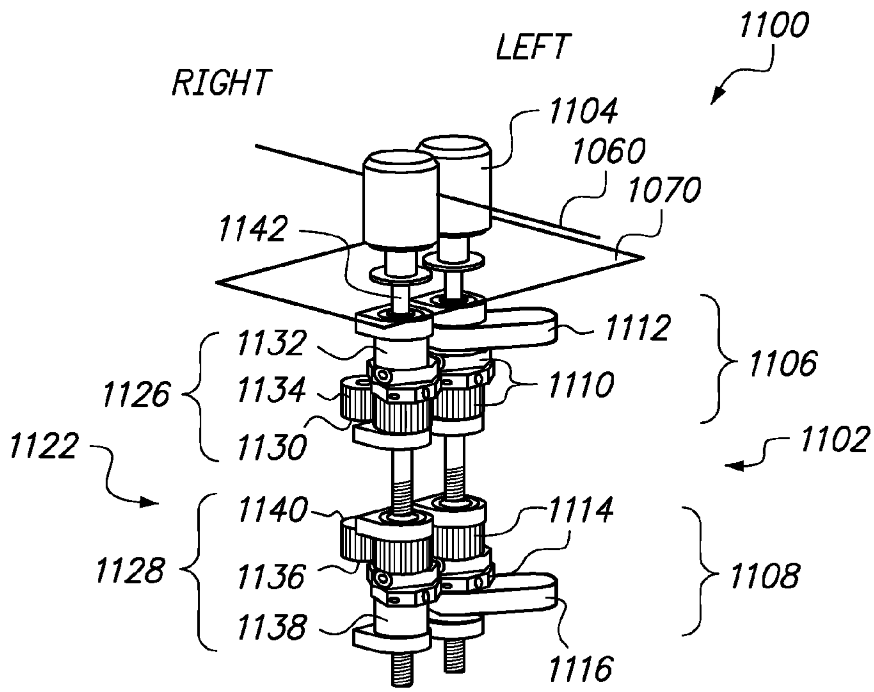


FIG. 79A

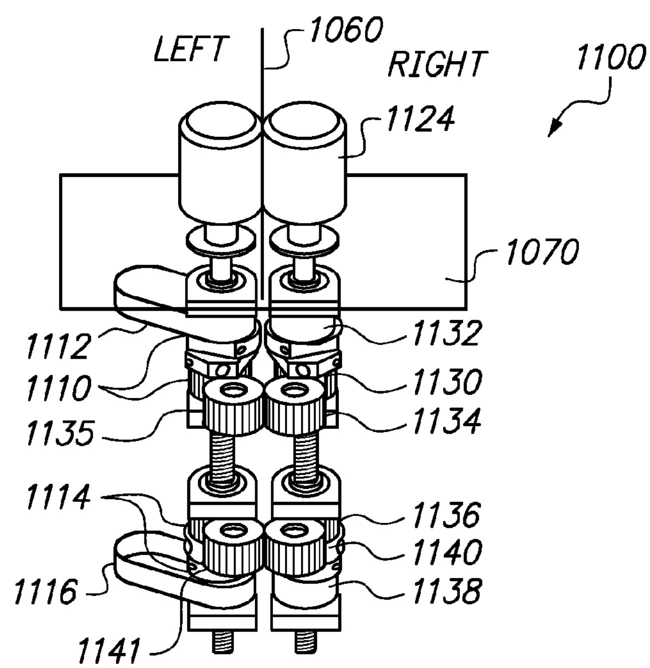


FIG. 79B

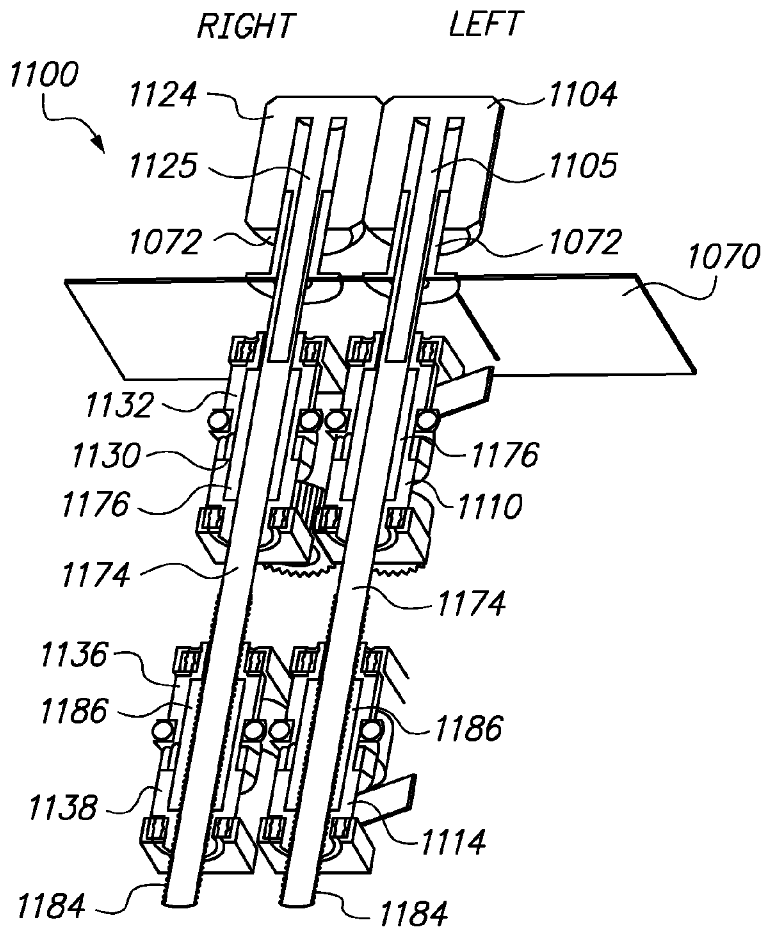


FIG. 79C

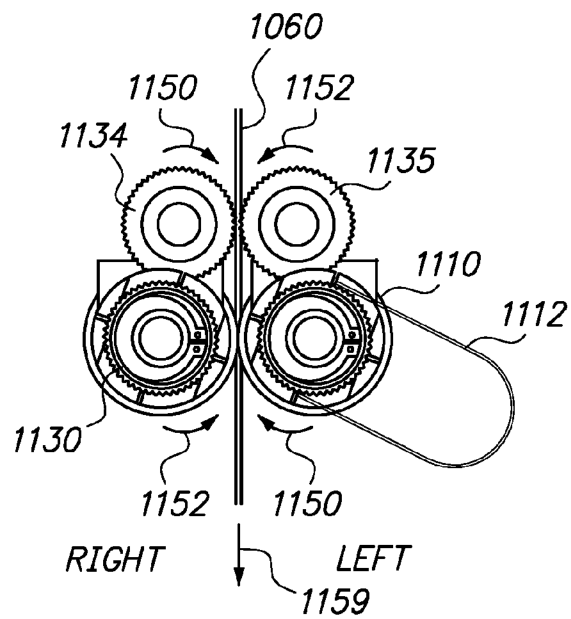


FIG. 79D

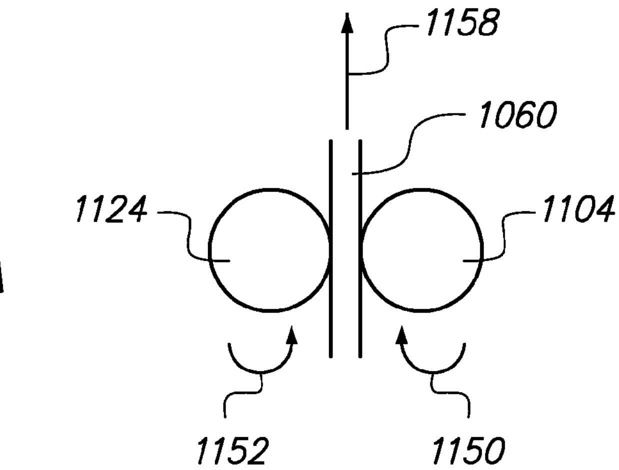


FIG. 80A

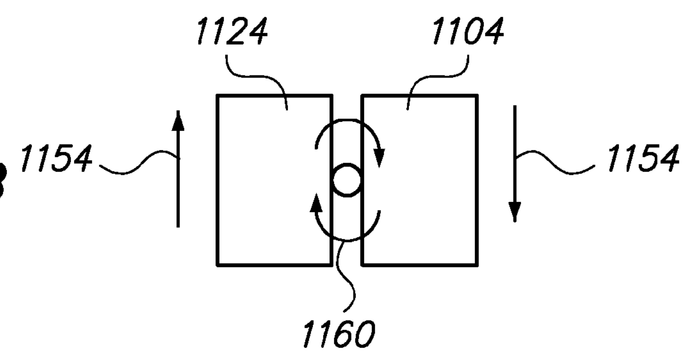


FIG. 80B

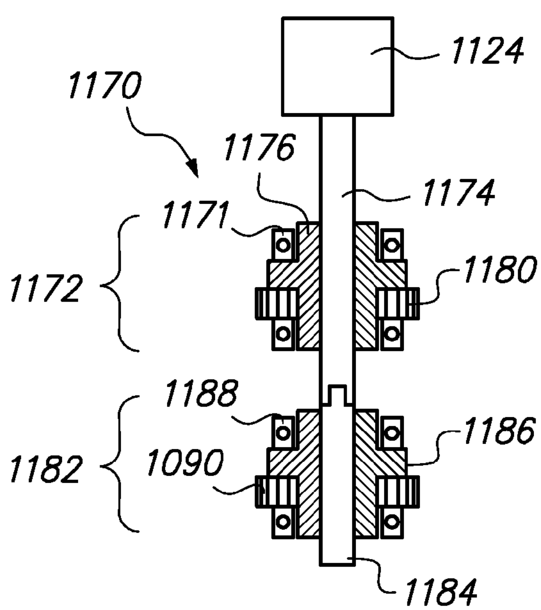


FIG. 81

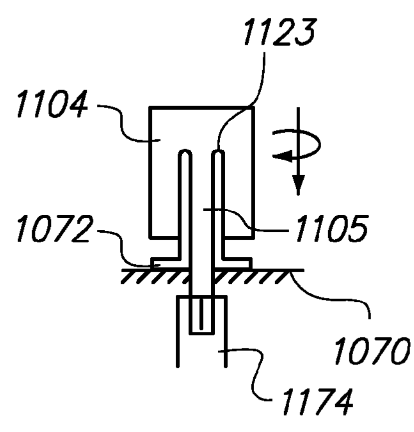


FIG. 82

FIG. 83

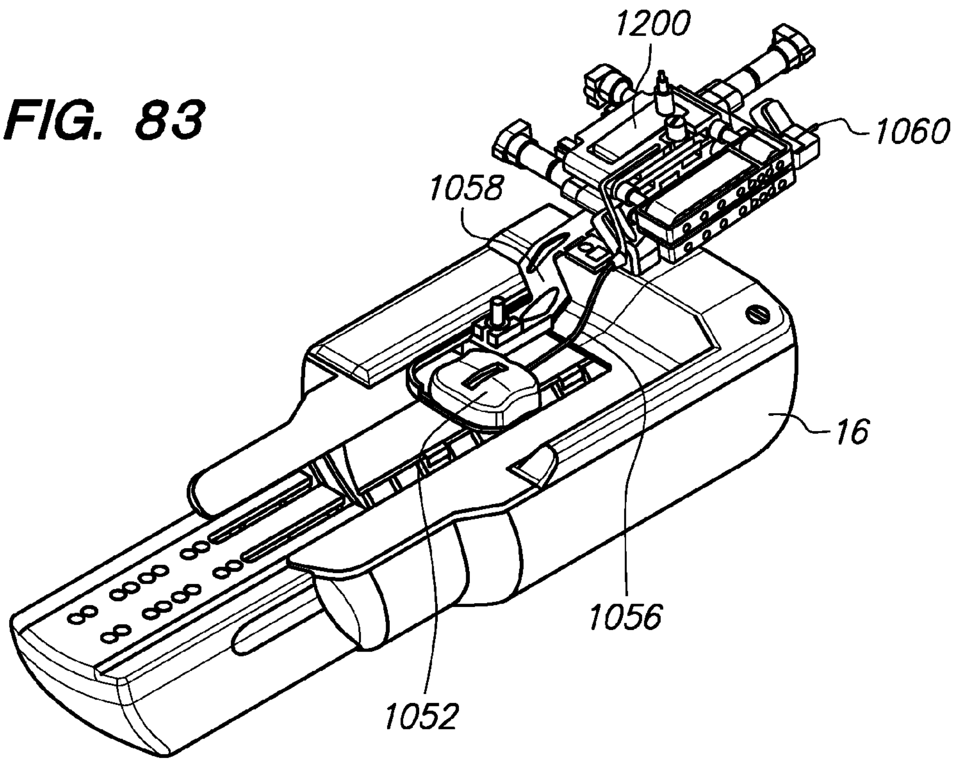
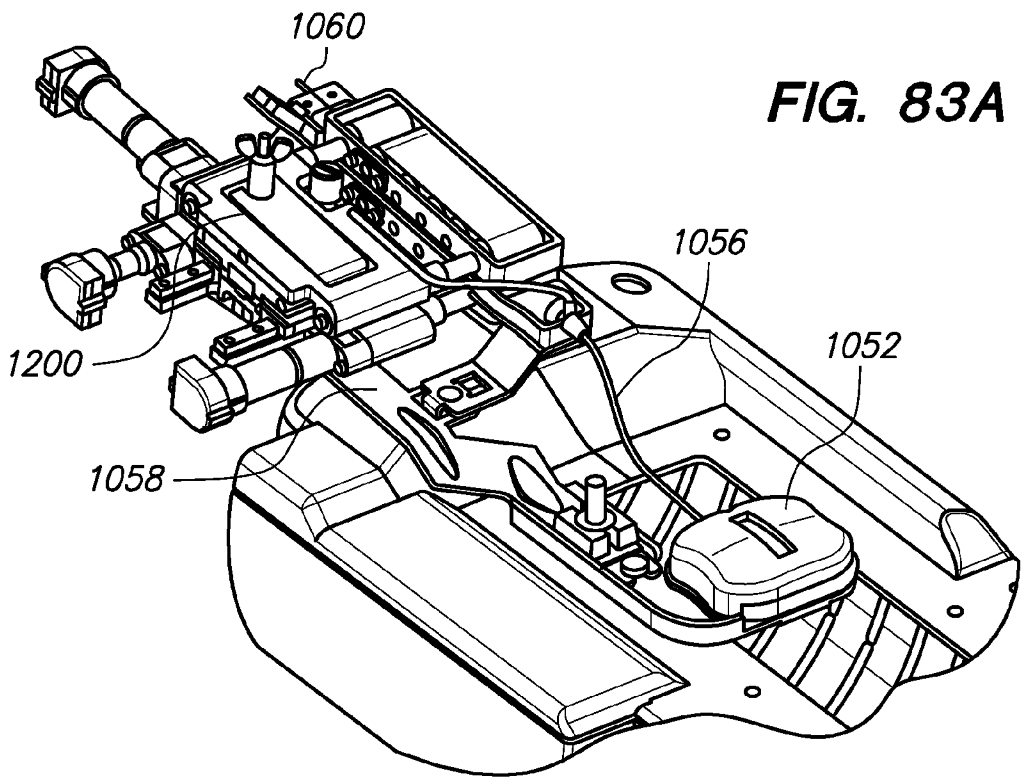


FIG. 83A



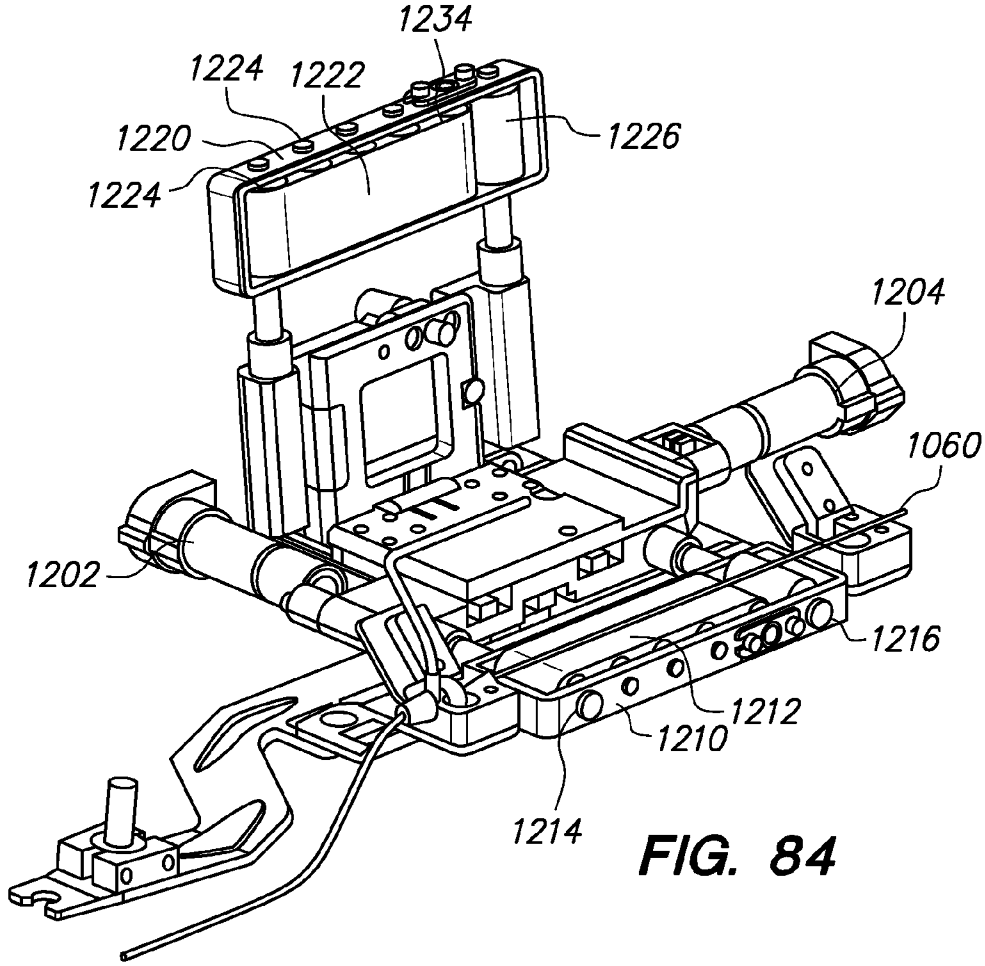


FIG. 84

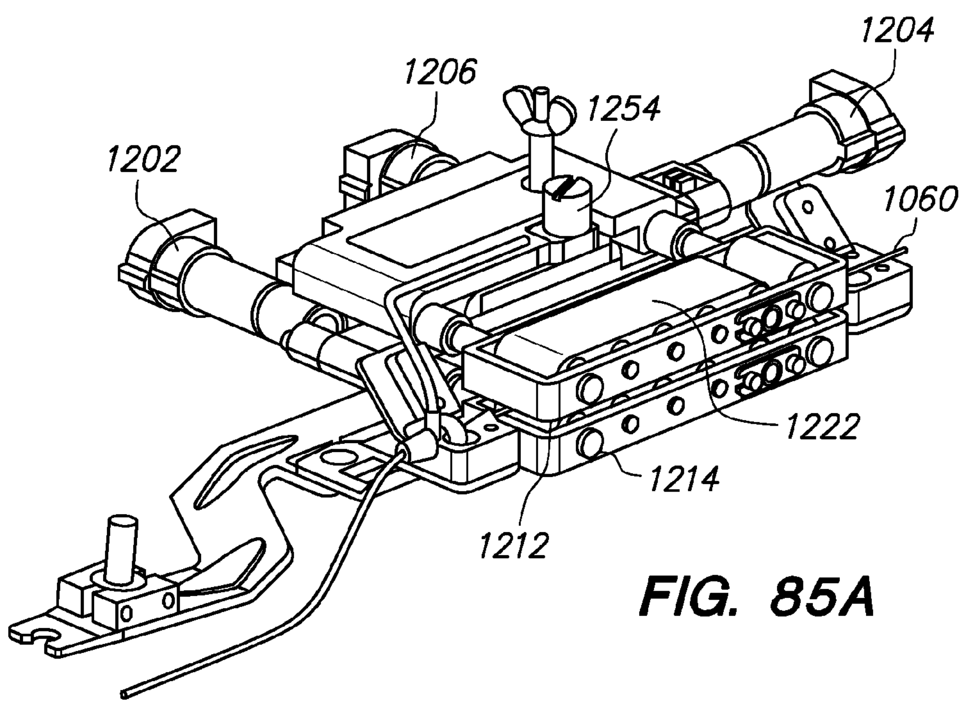


FIG. 85A

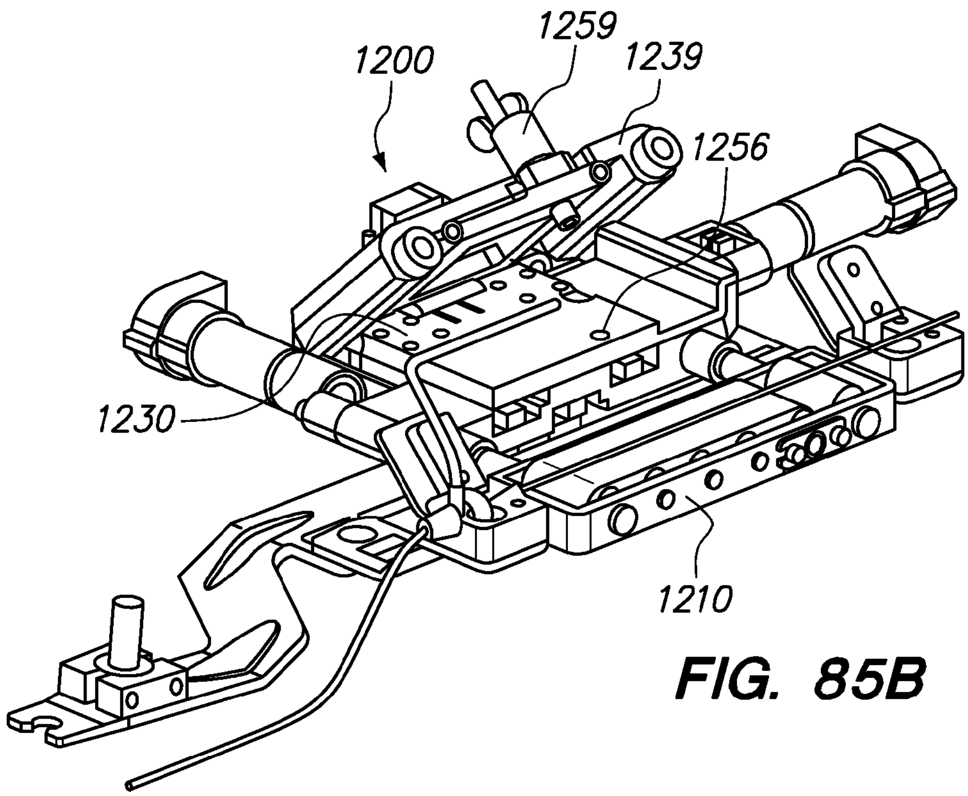


FIG. 85B

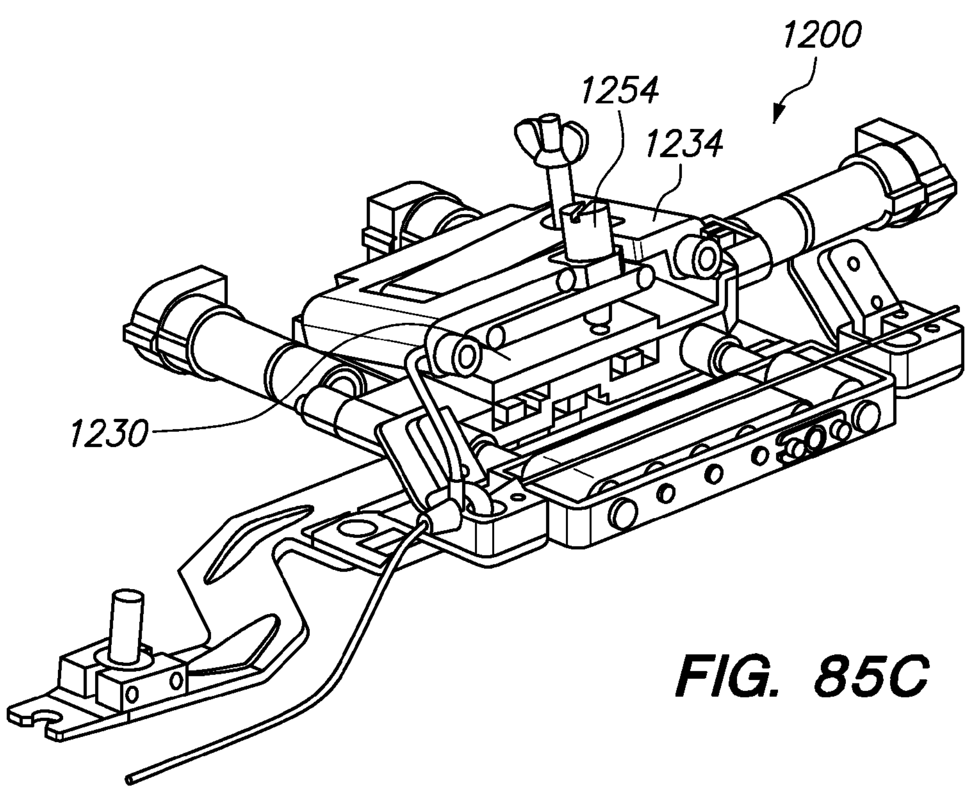


FIG. 85C

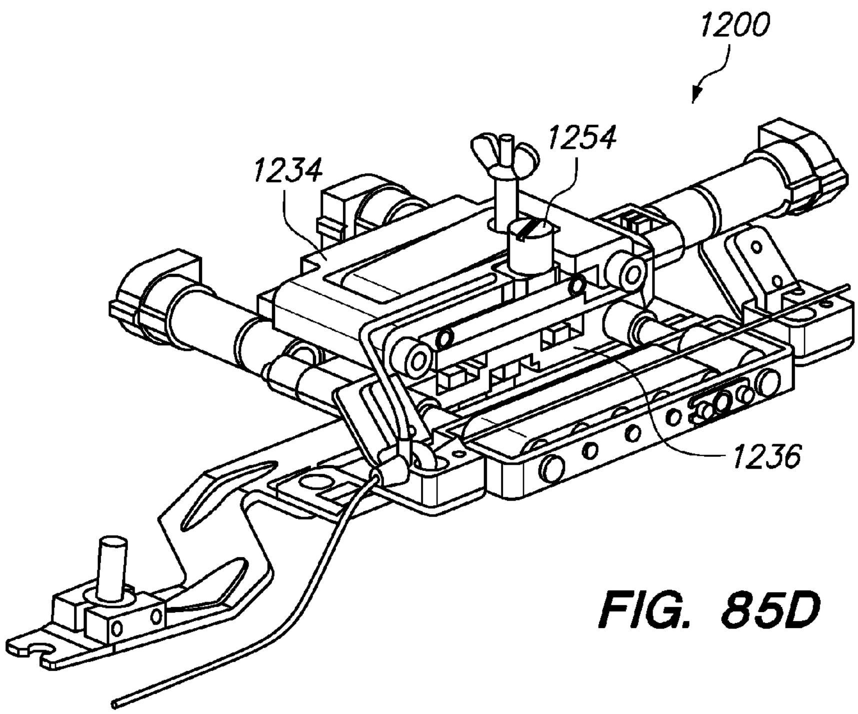


FIG. 85D

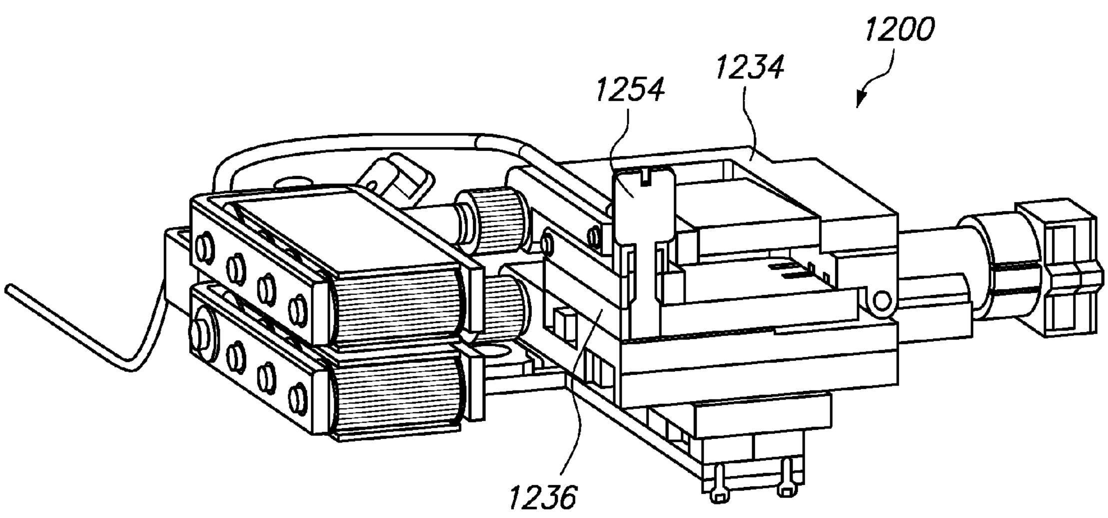


FIG. 85E

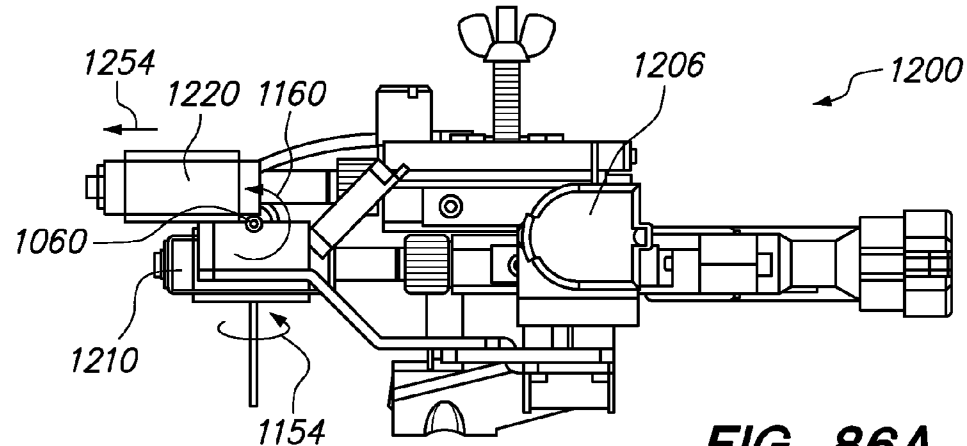


FIG. 86A

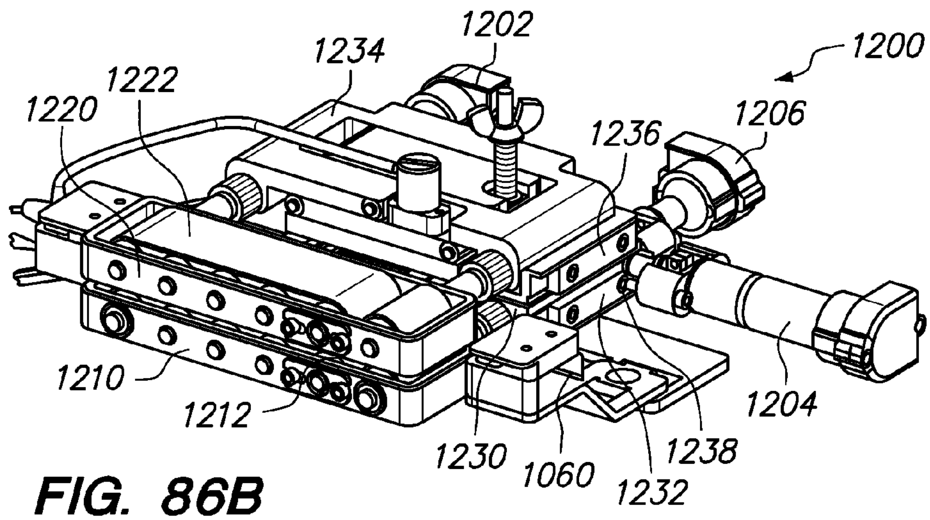


FIG. 86B

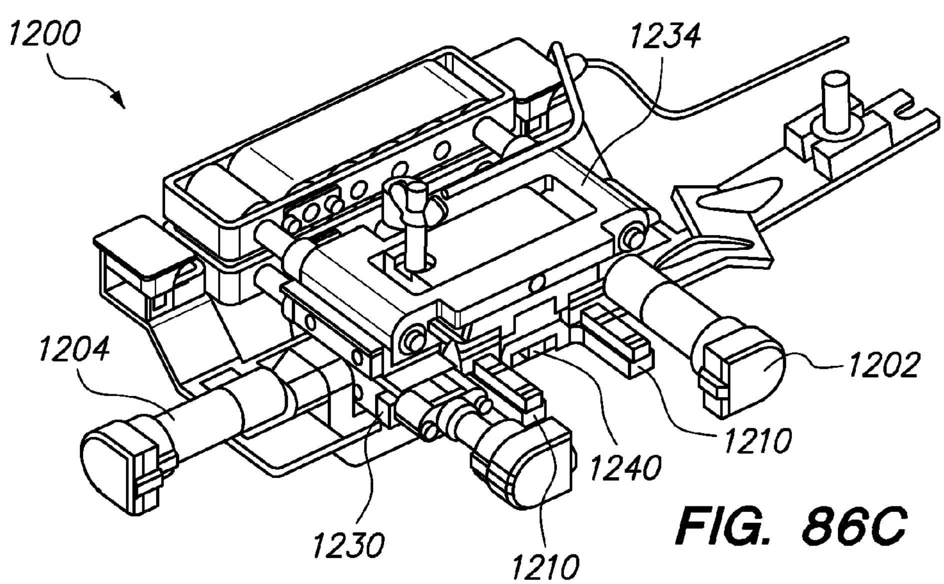


FIG. 86C

FIG. 87A

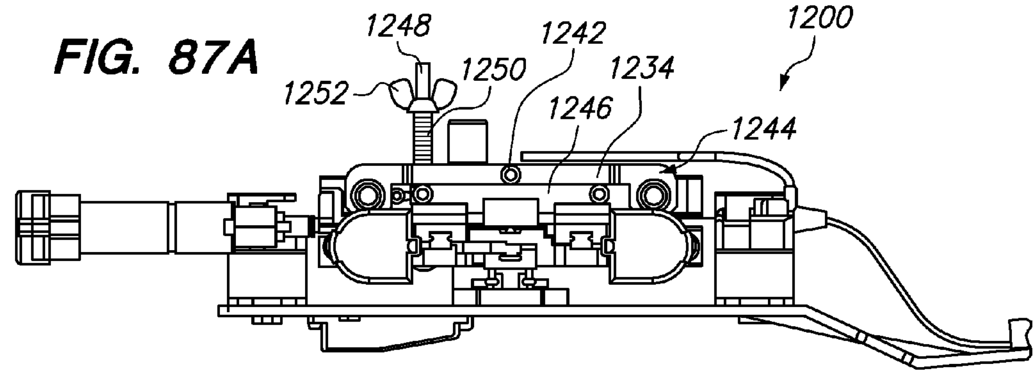


FIG. 87B

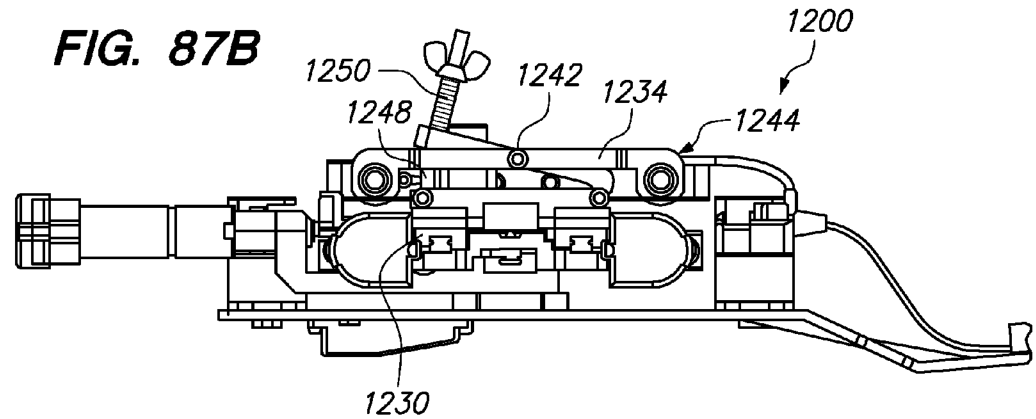
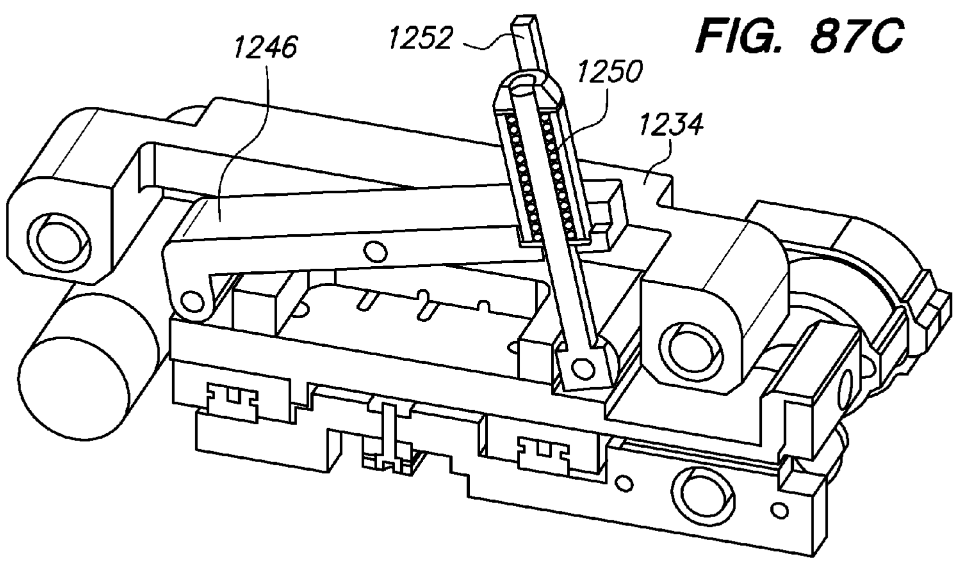


FIG. 87C



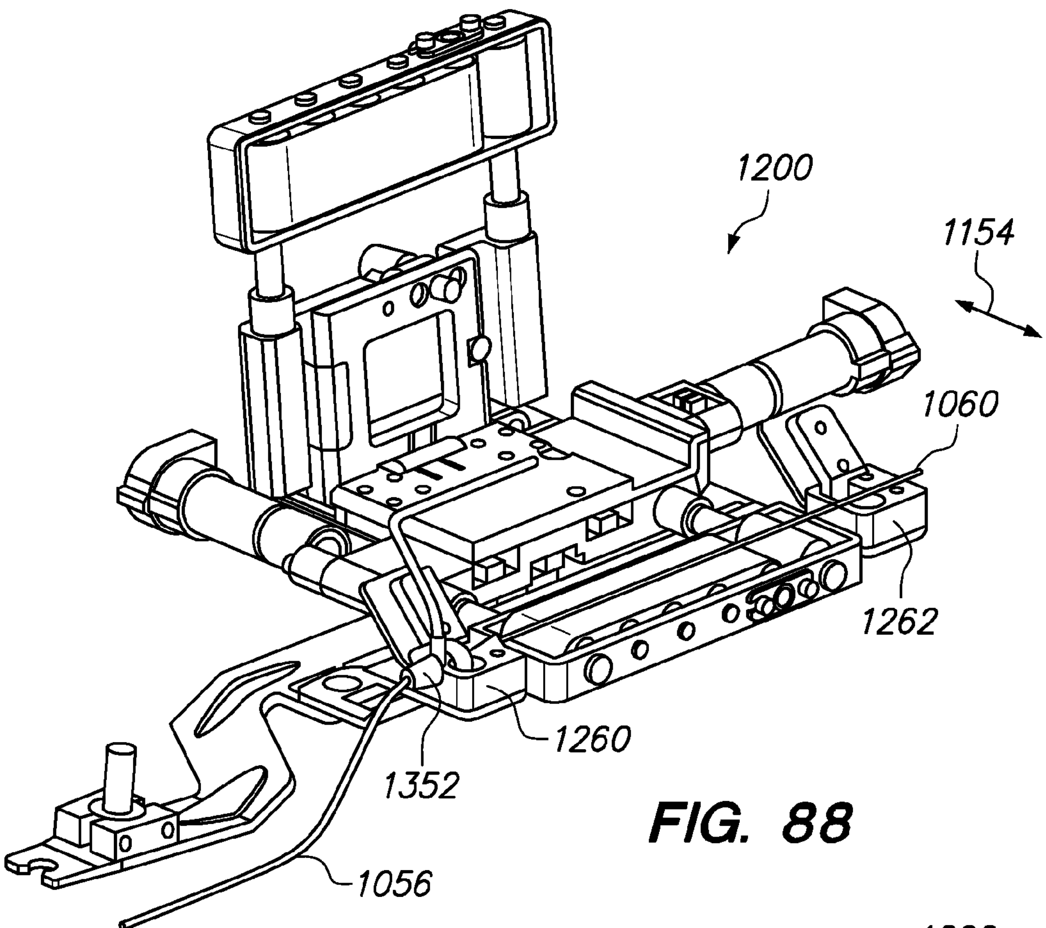


FIG. 88

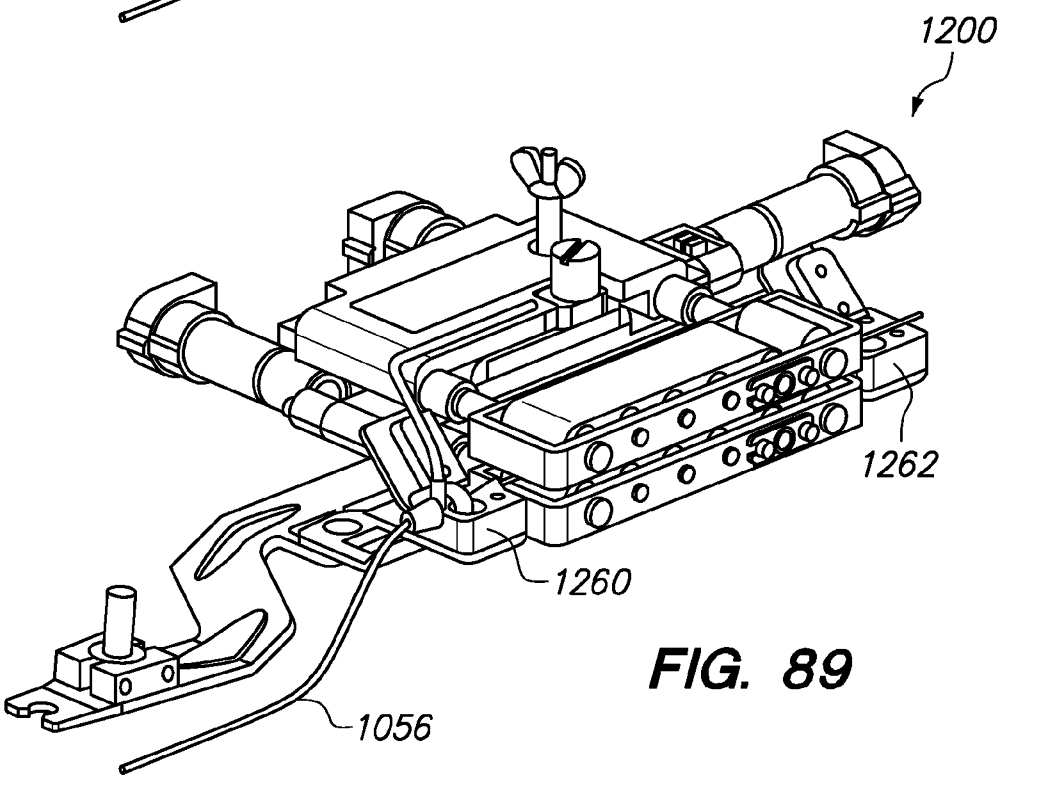


FIG. 89

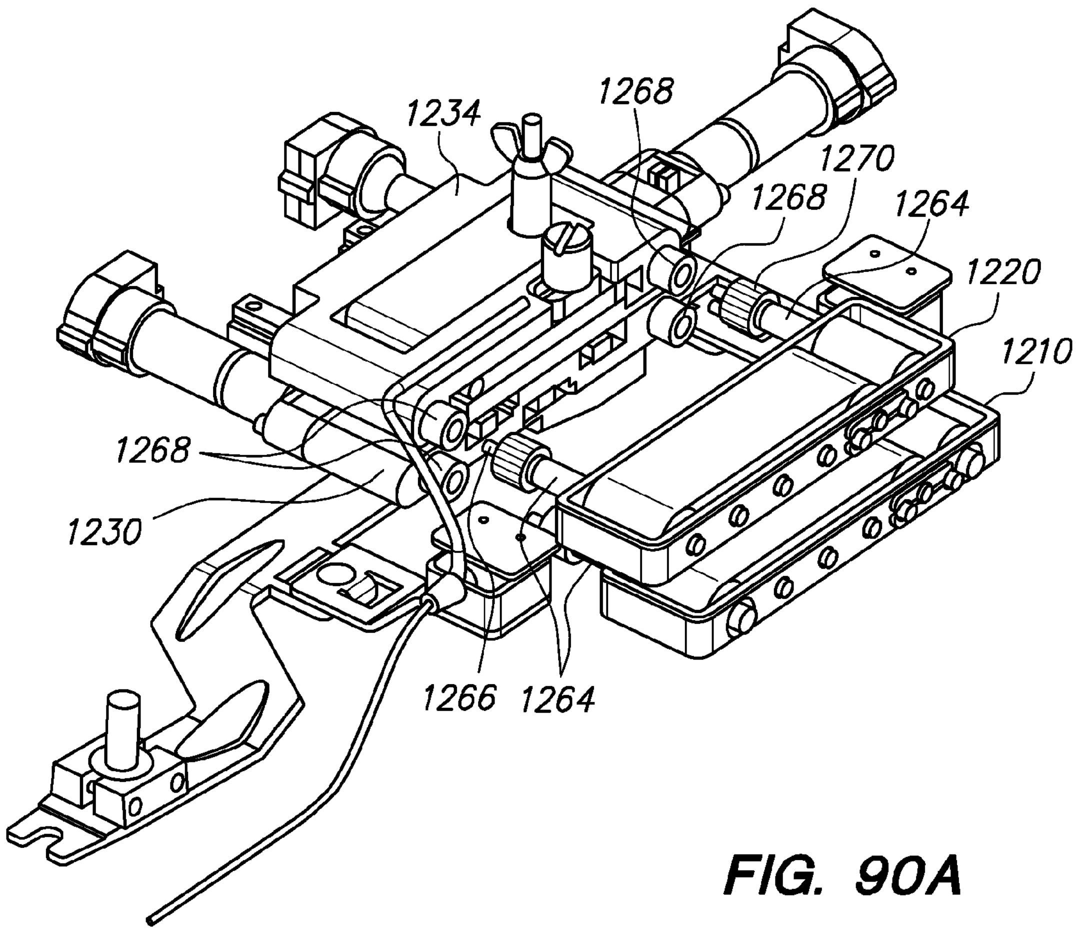


FIG. 90A

FIG. 90B

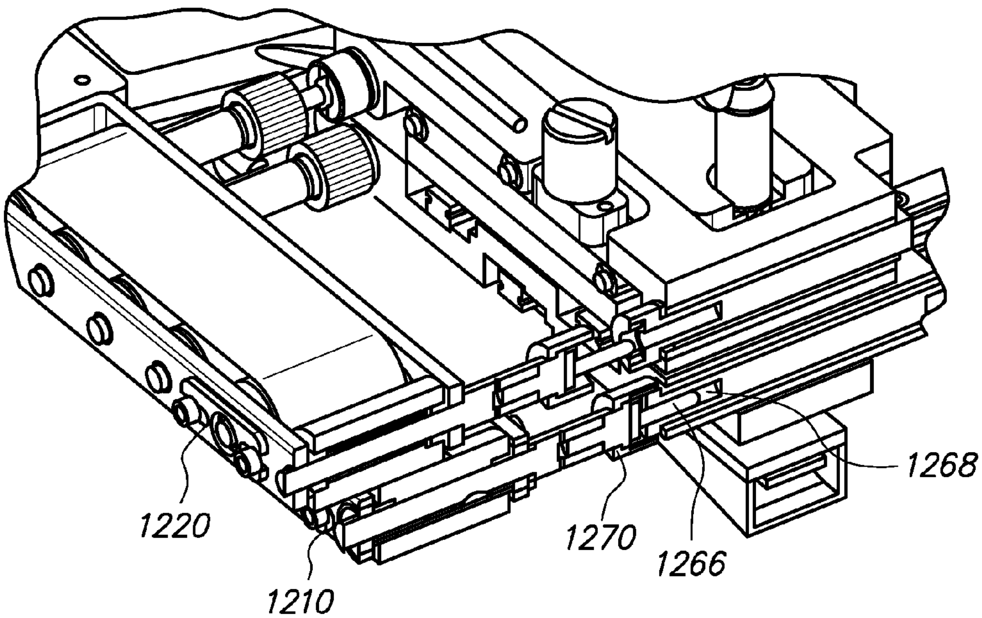
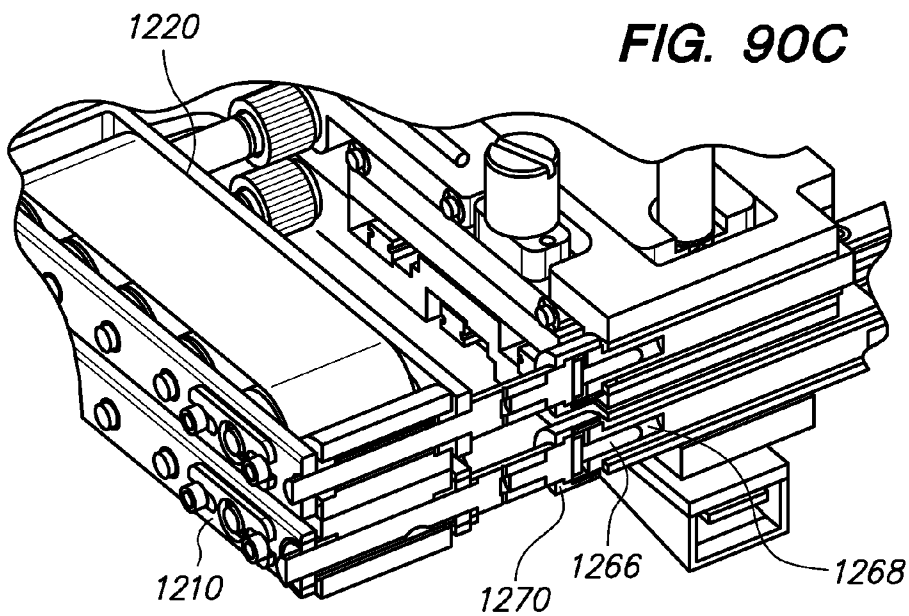


FIG. 90C



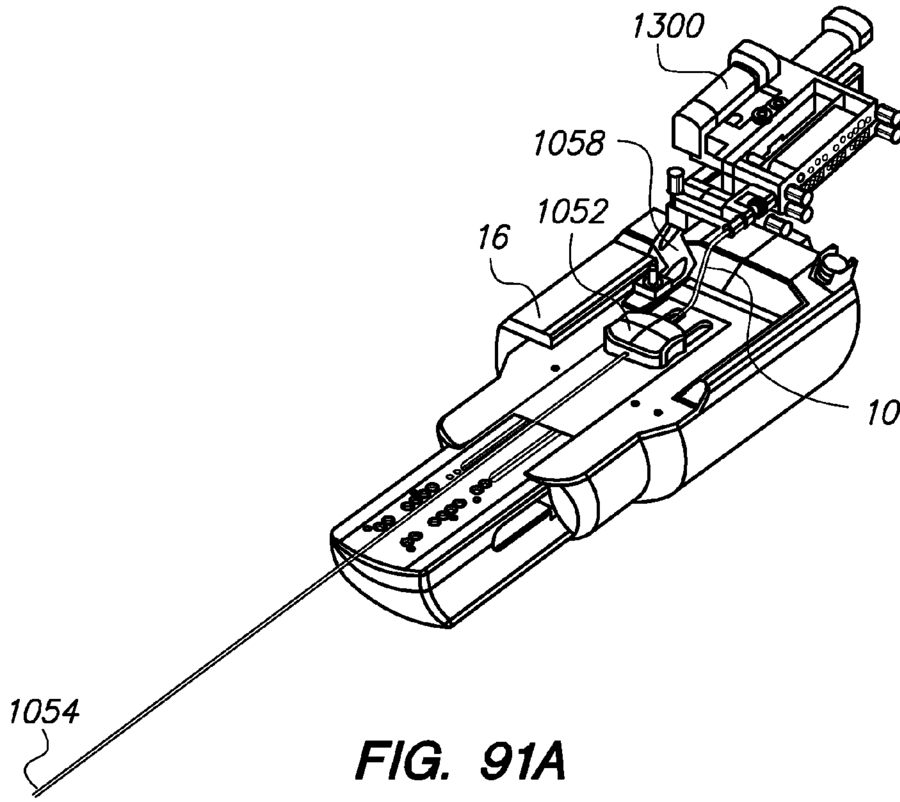


FIG. 91A

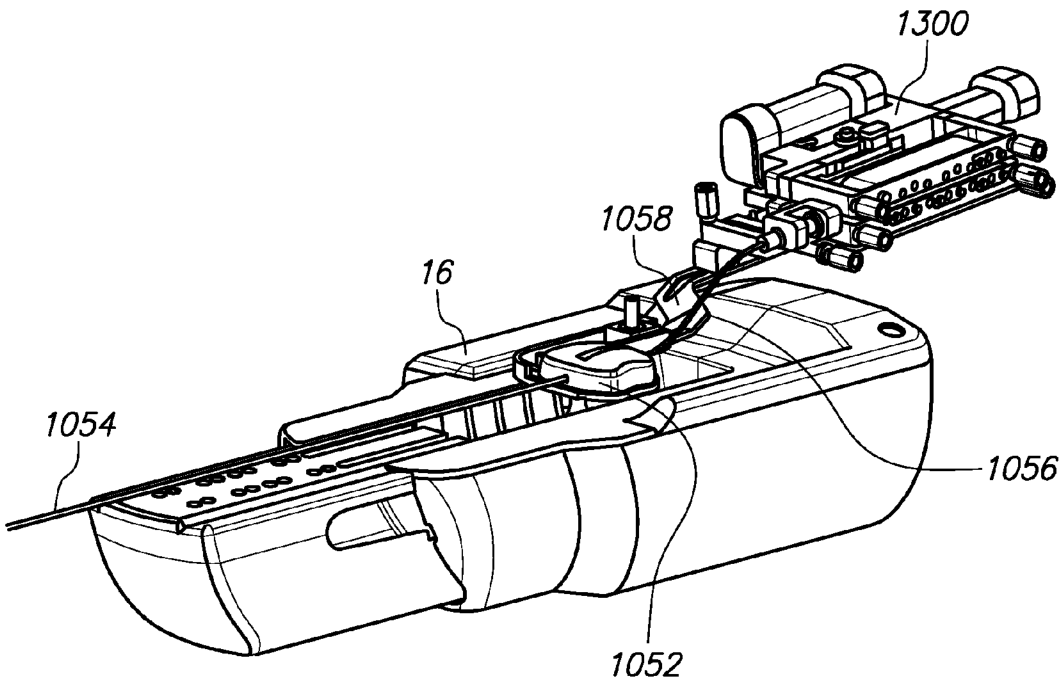


FIG. 91B

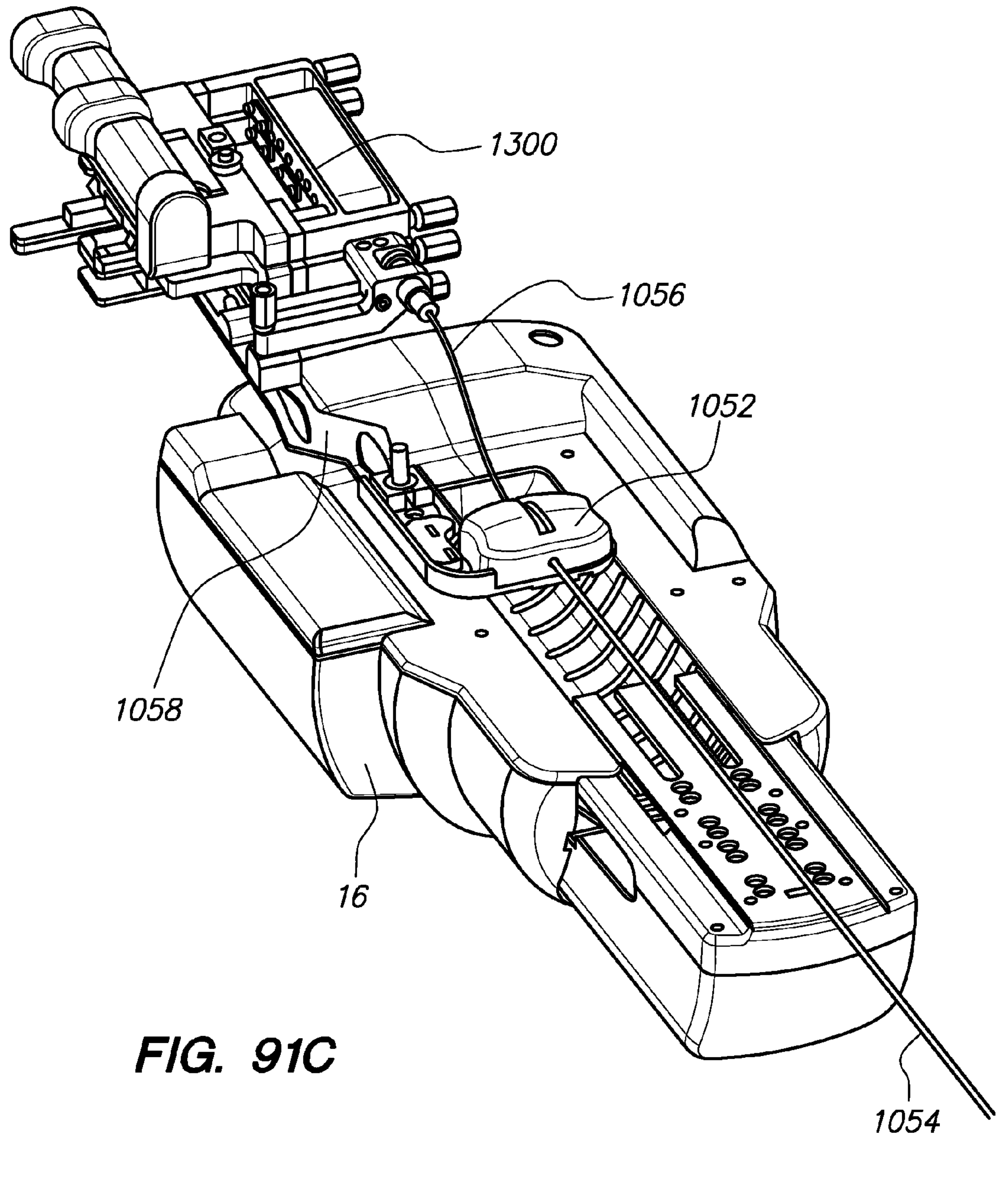
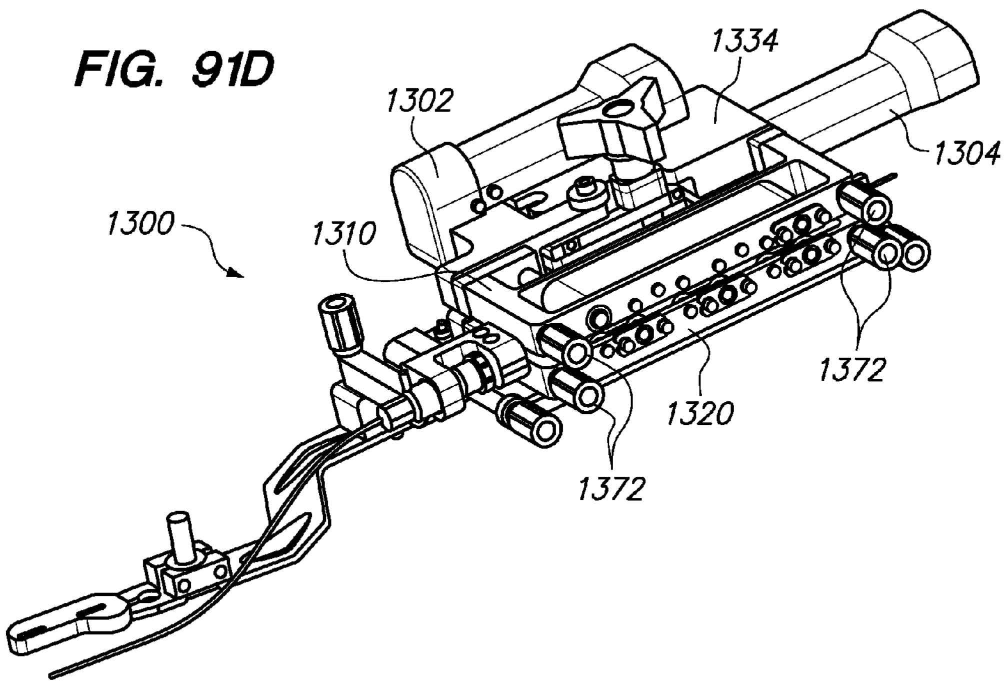


FIG. 91C

FIG. 91D



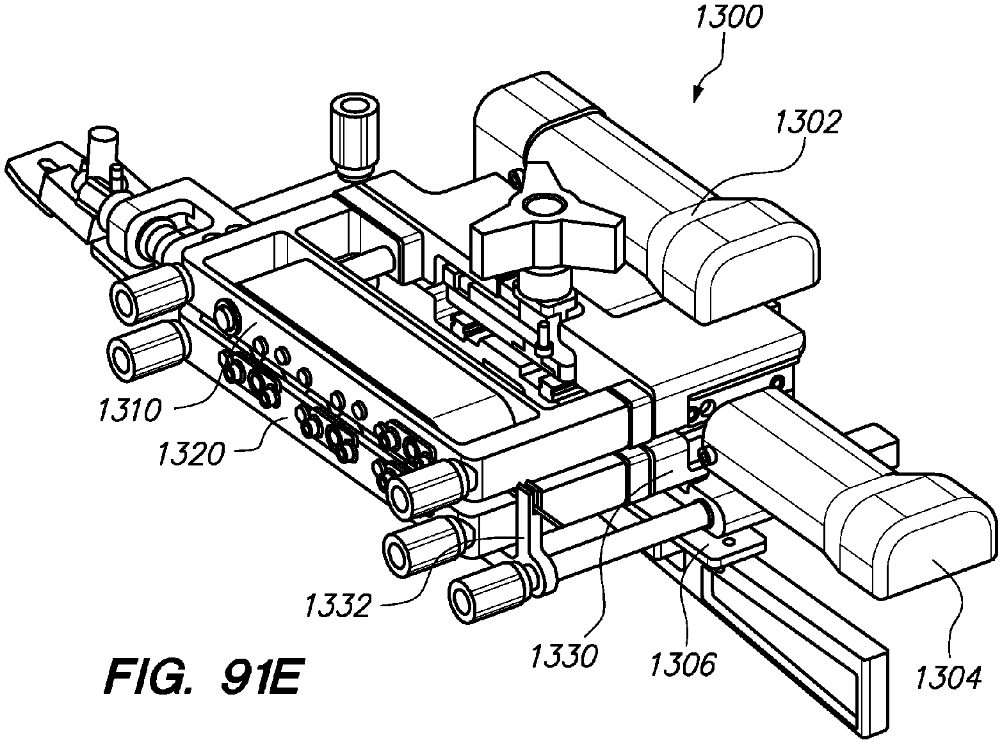


FIG. 91E

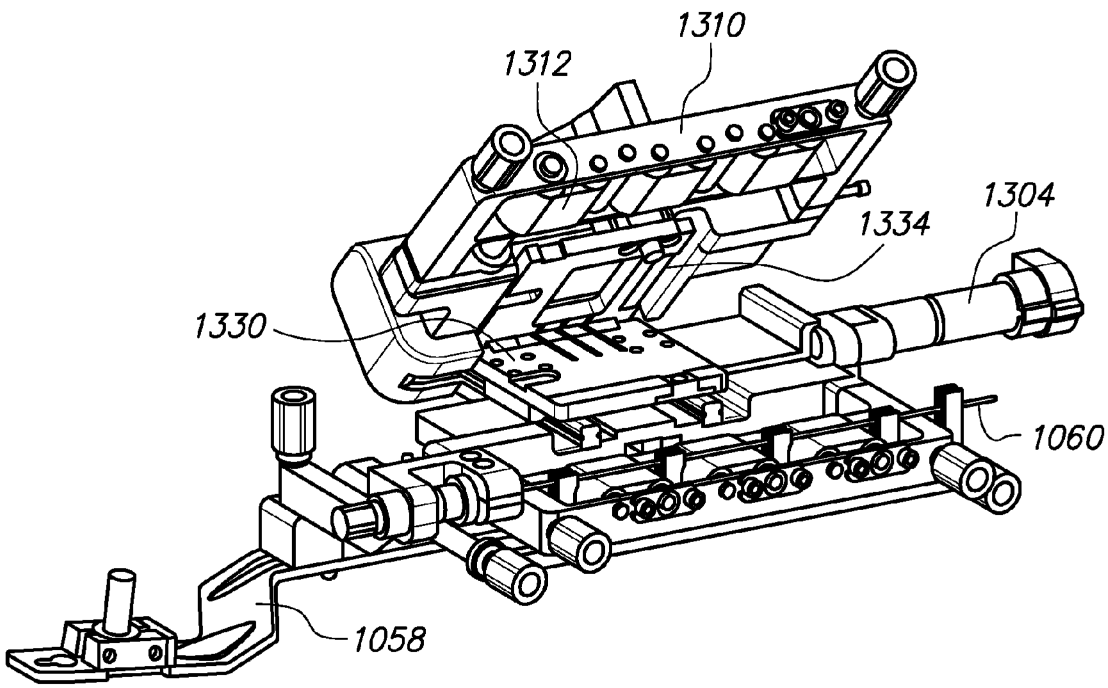


FIG. 91F

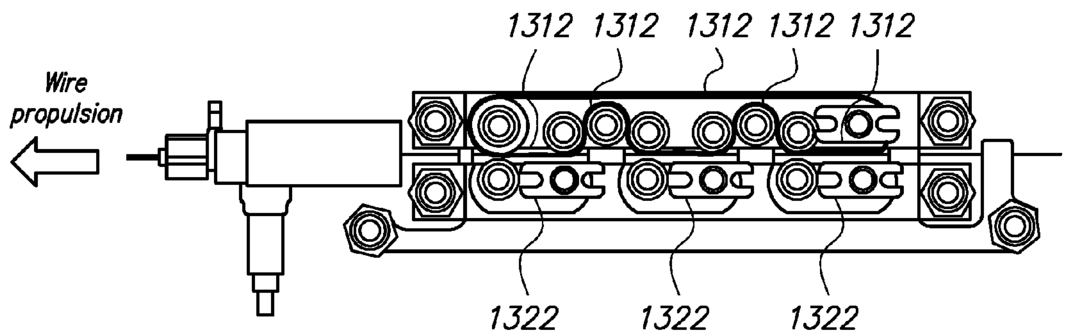


FIG. 91G

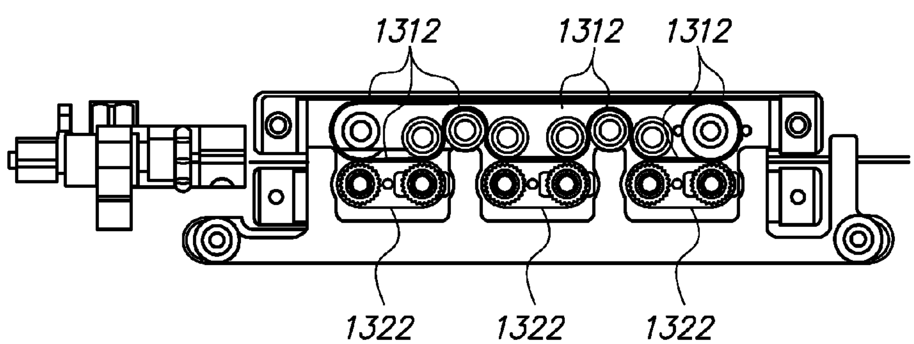


FIG. 91H

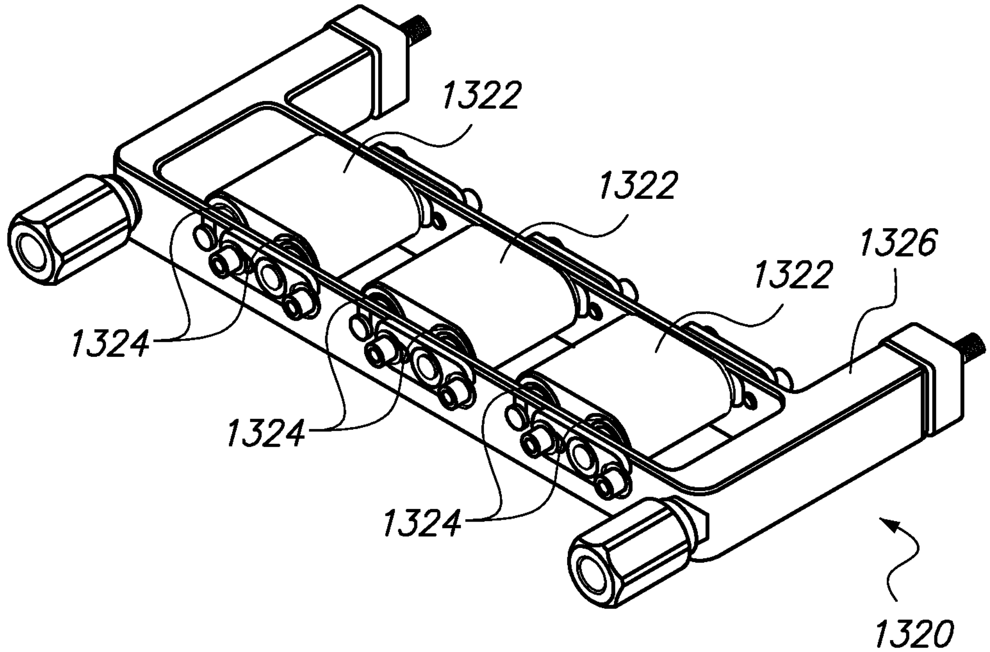


FIG. 92A

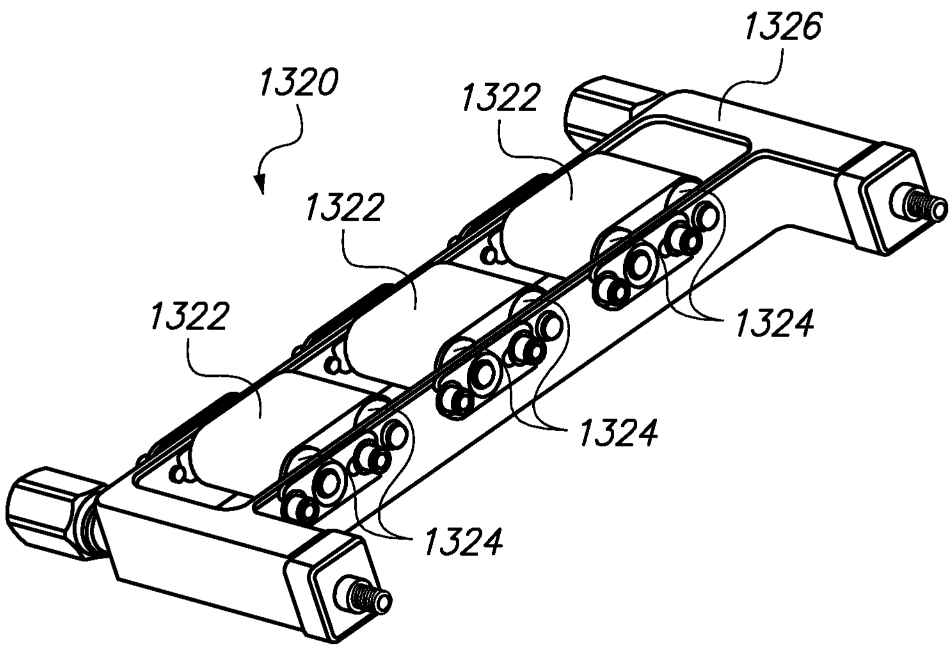


FIG. 92B

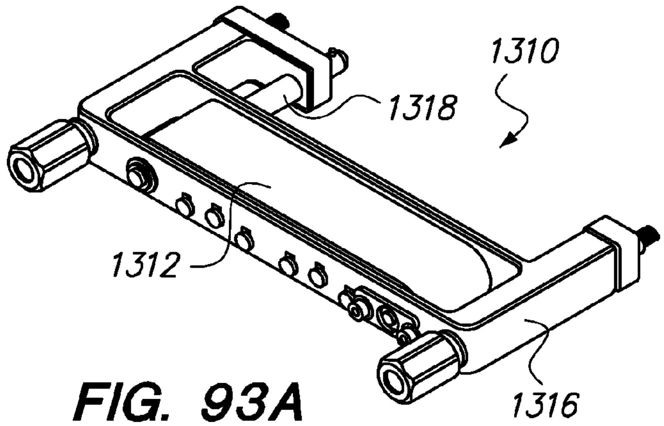


FIG. 93A

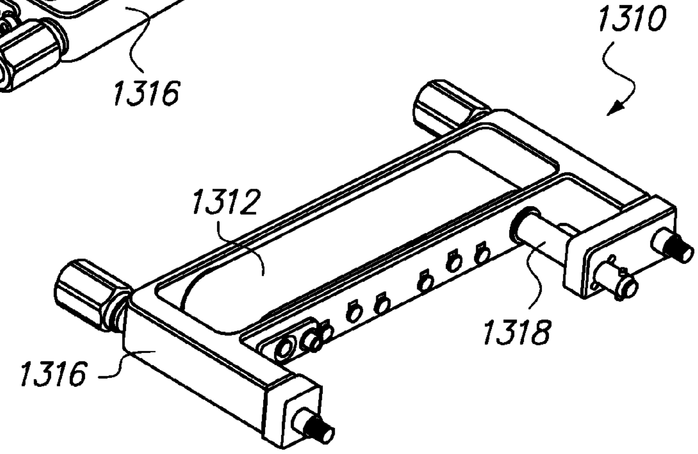


FIG. 93B

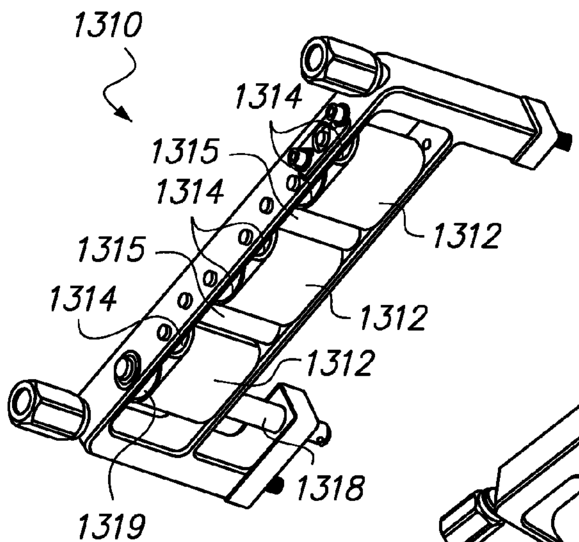


FIG. 93C

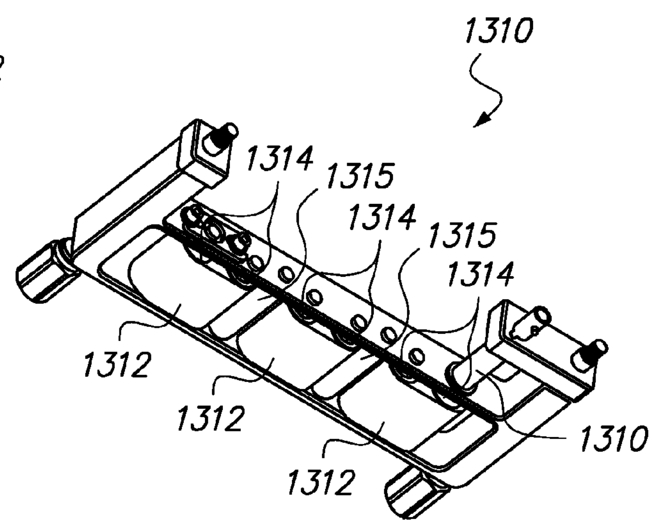


FIG. 93D

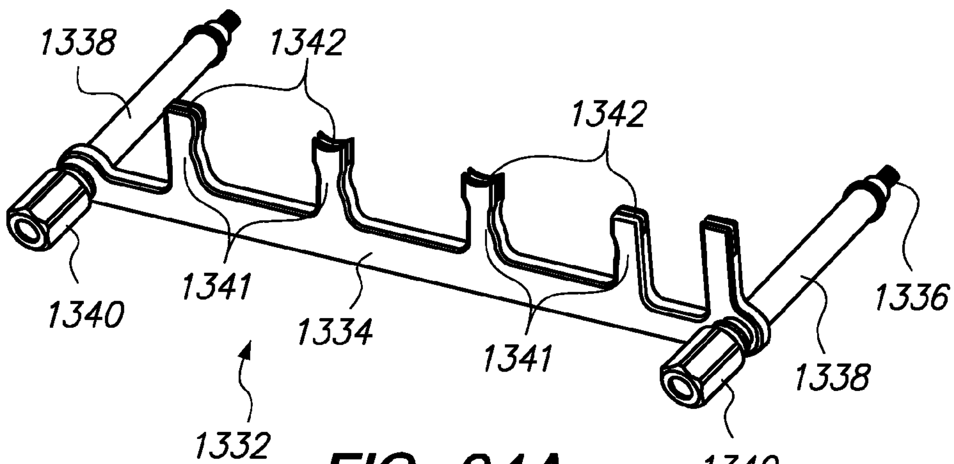


FIG. 94A

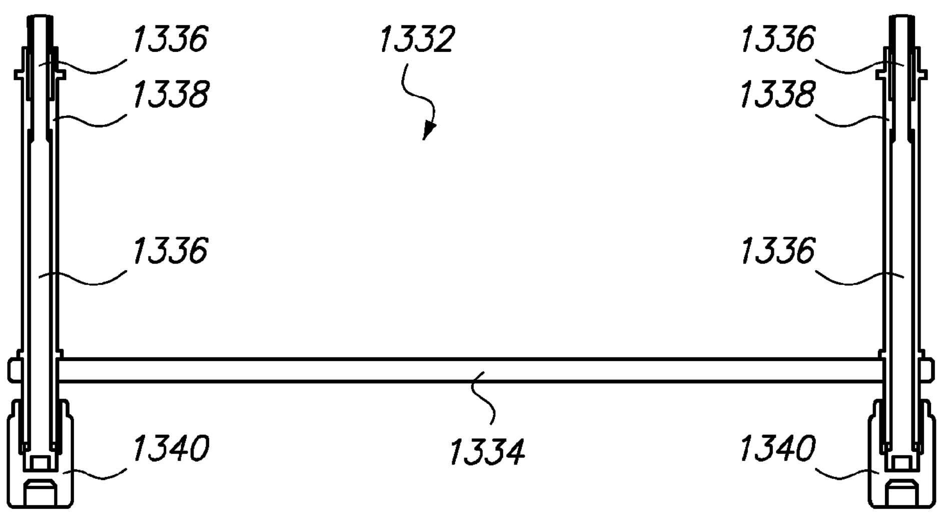


FIG. 94B

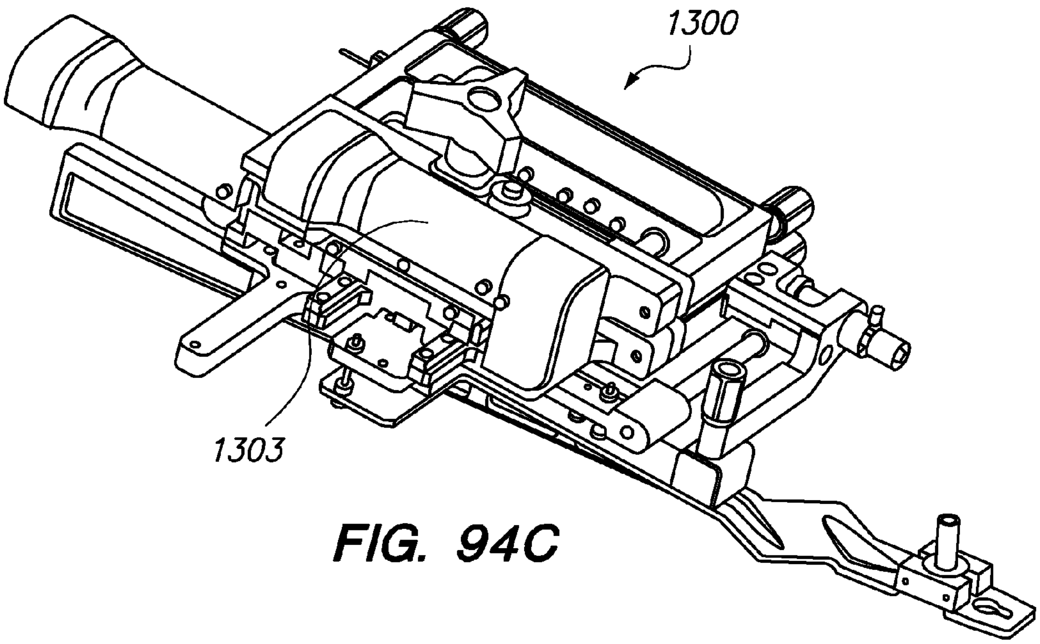


FIG. 94C

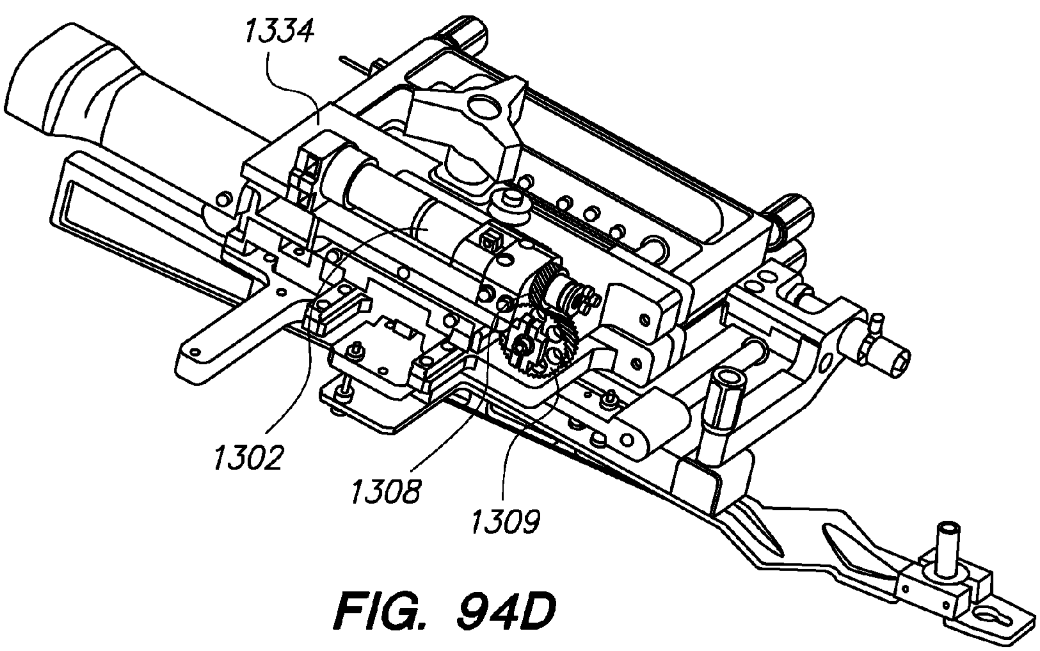


FIG. 94D

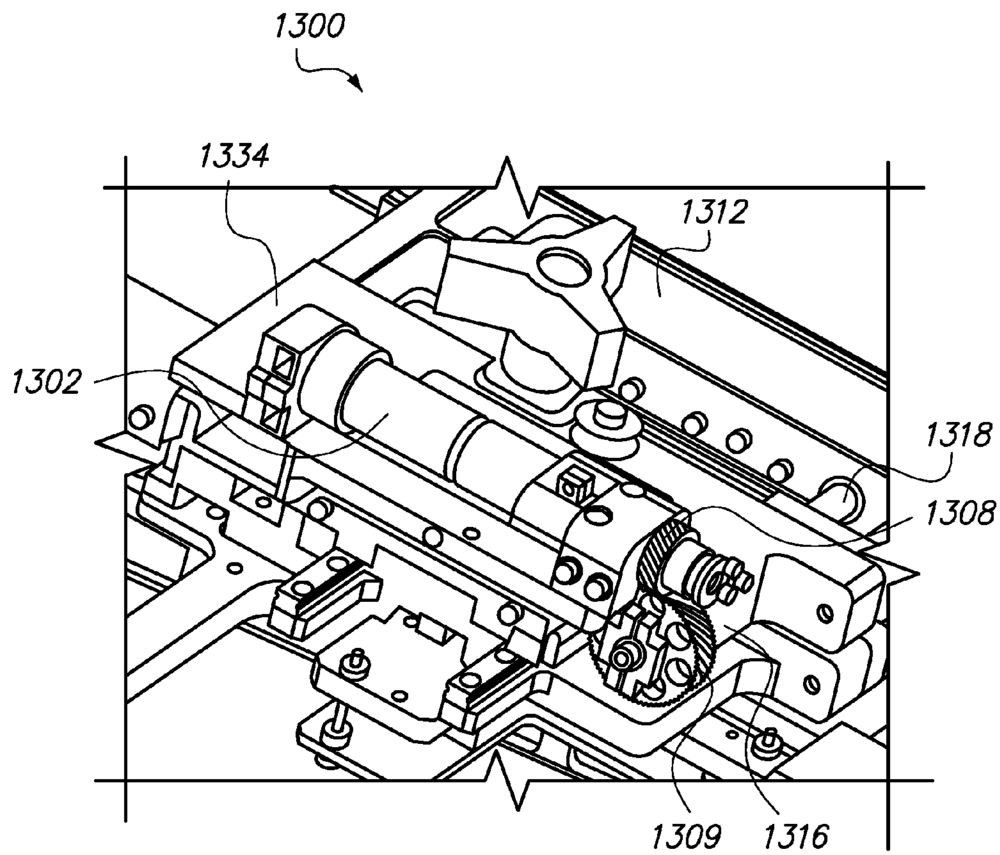


FIG. 94E

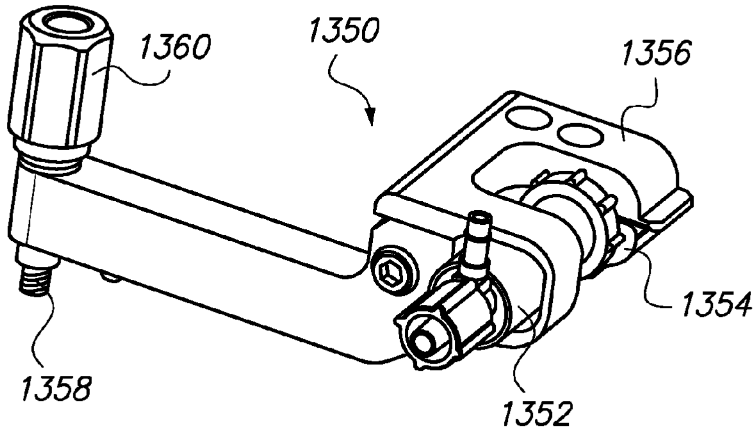


FIG. 95A

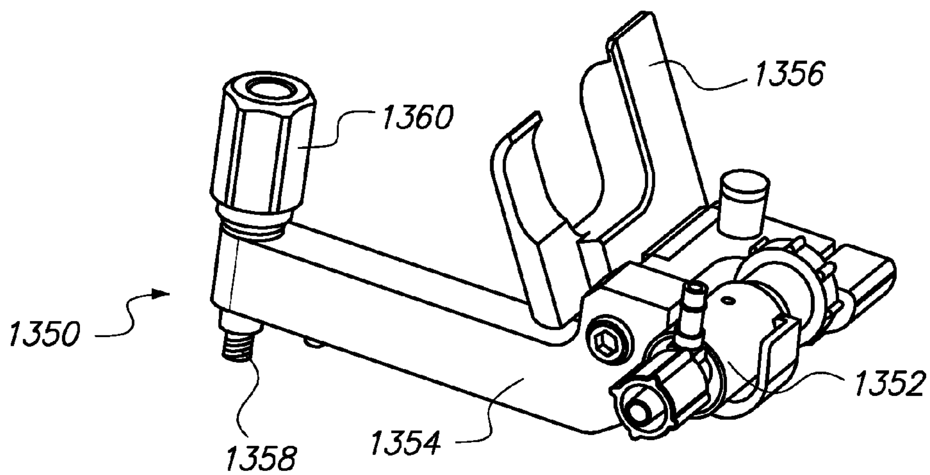


FIG. 95B

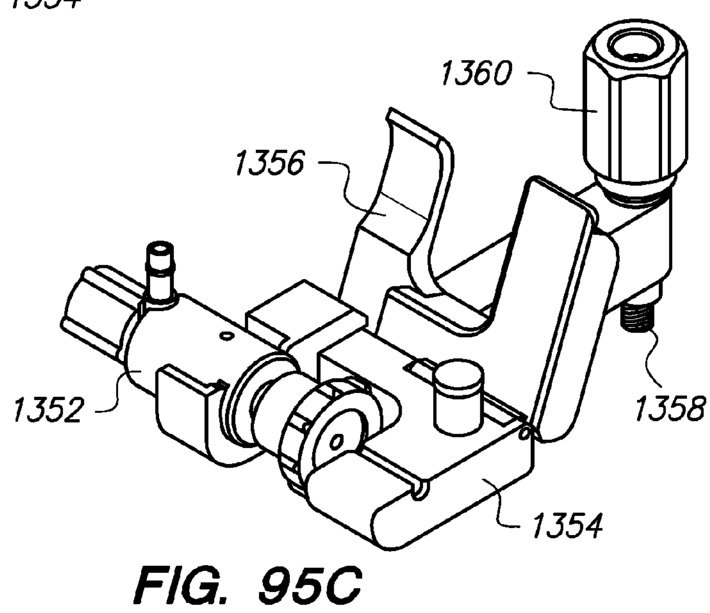


FIG. 95C

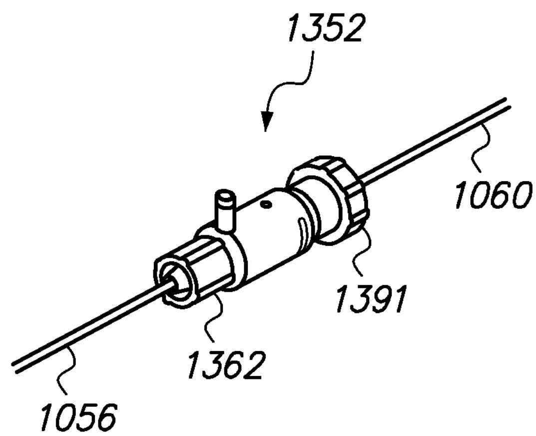


FIG. 95D

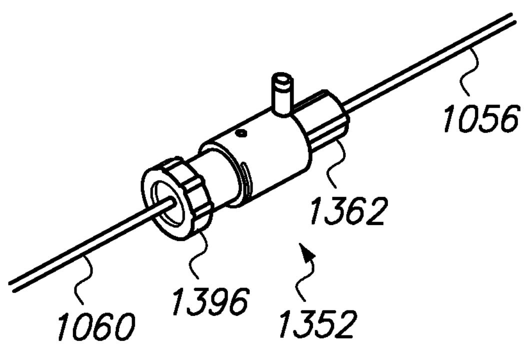


FIG. 95E

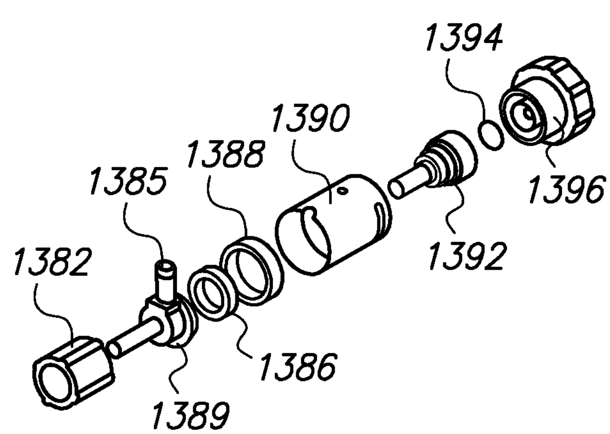


FIG. 95F

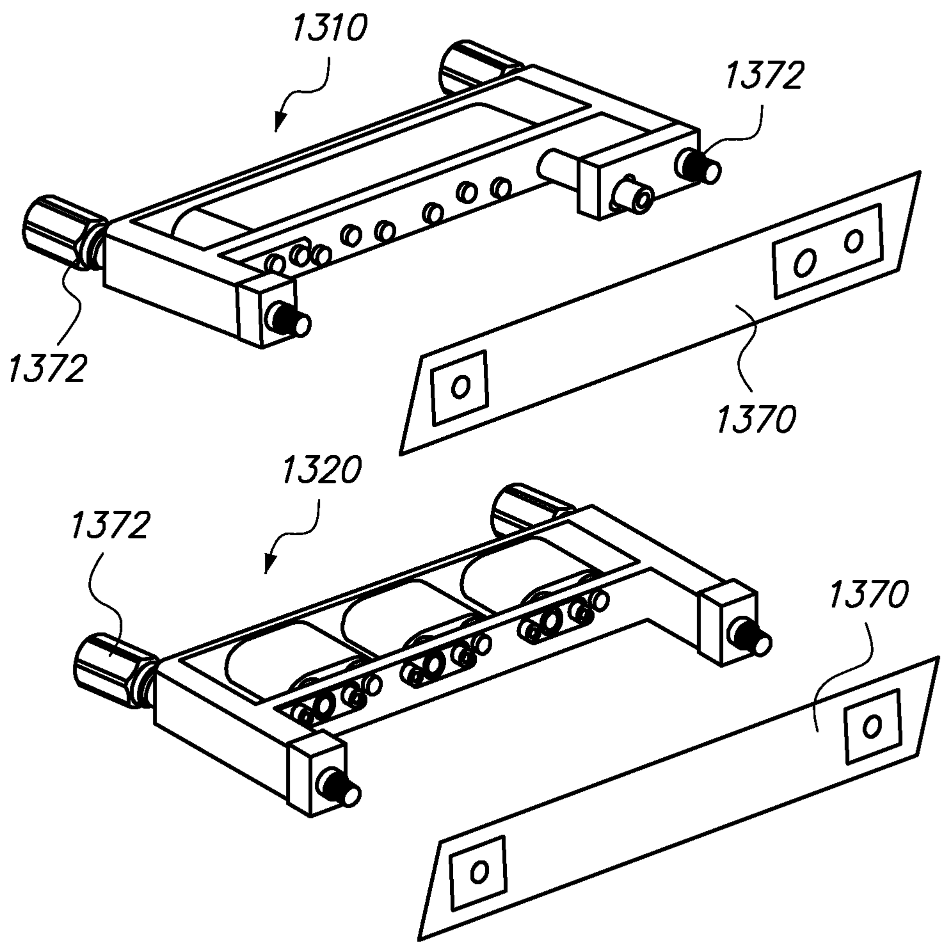


FIG. 96

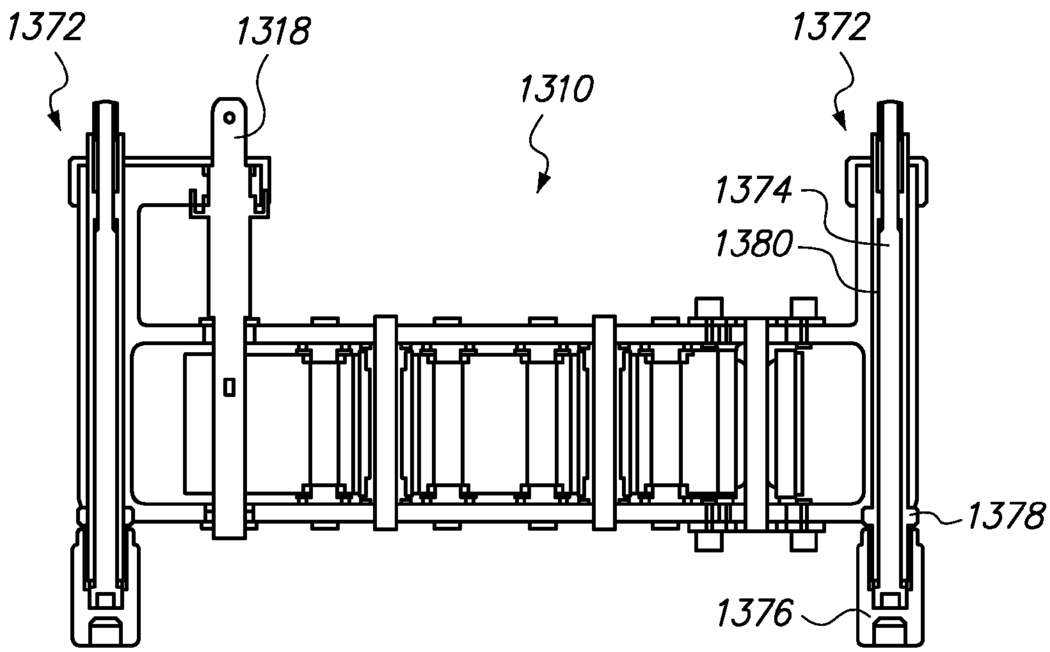


FIG. 96A

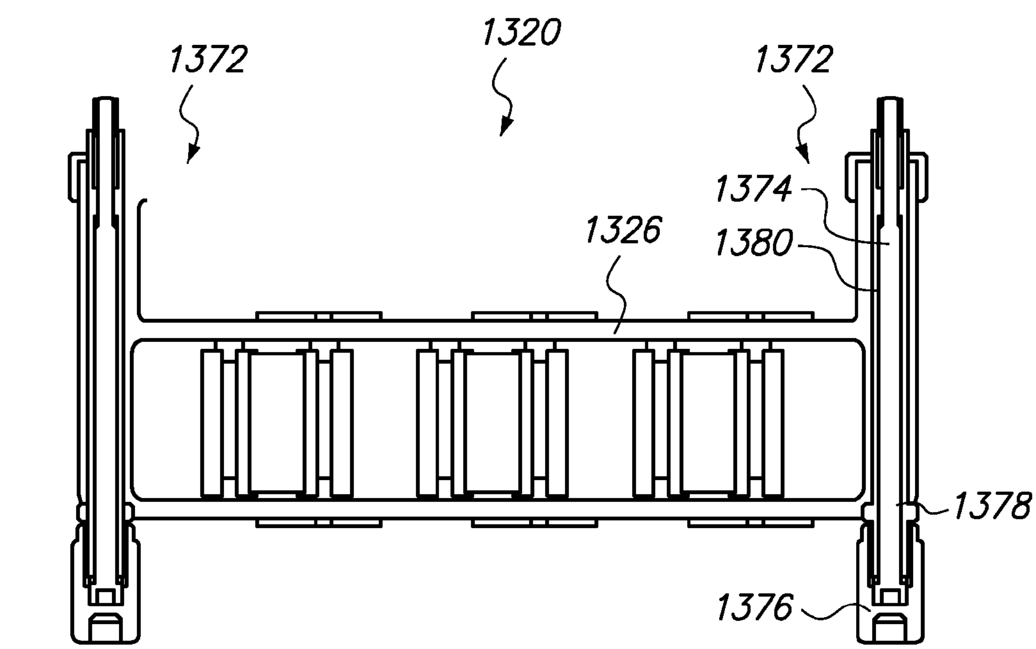


FIG. 96B

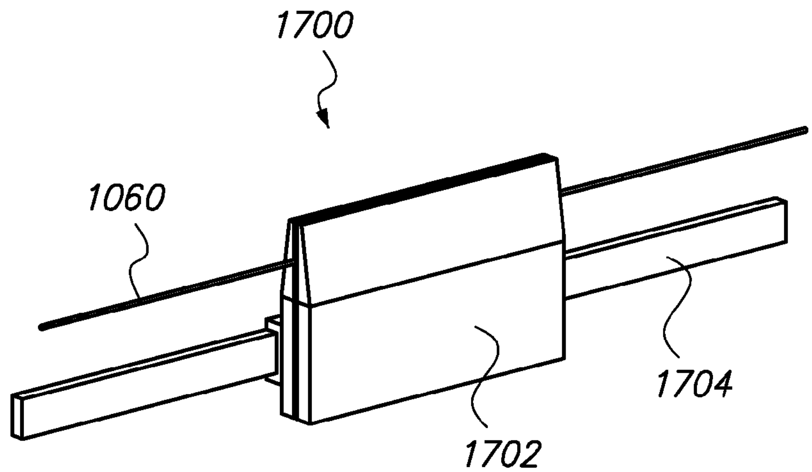


FIG. 96C

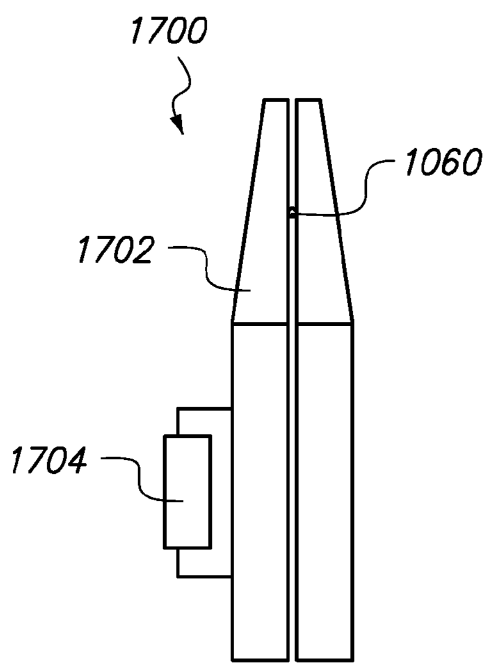


FIG. 96D

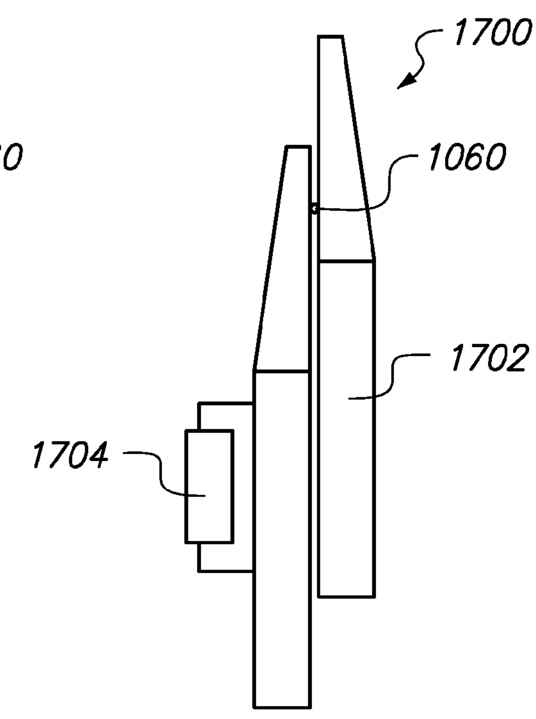


FIG. 96E

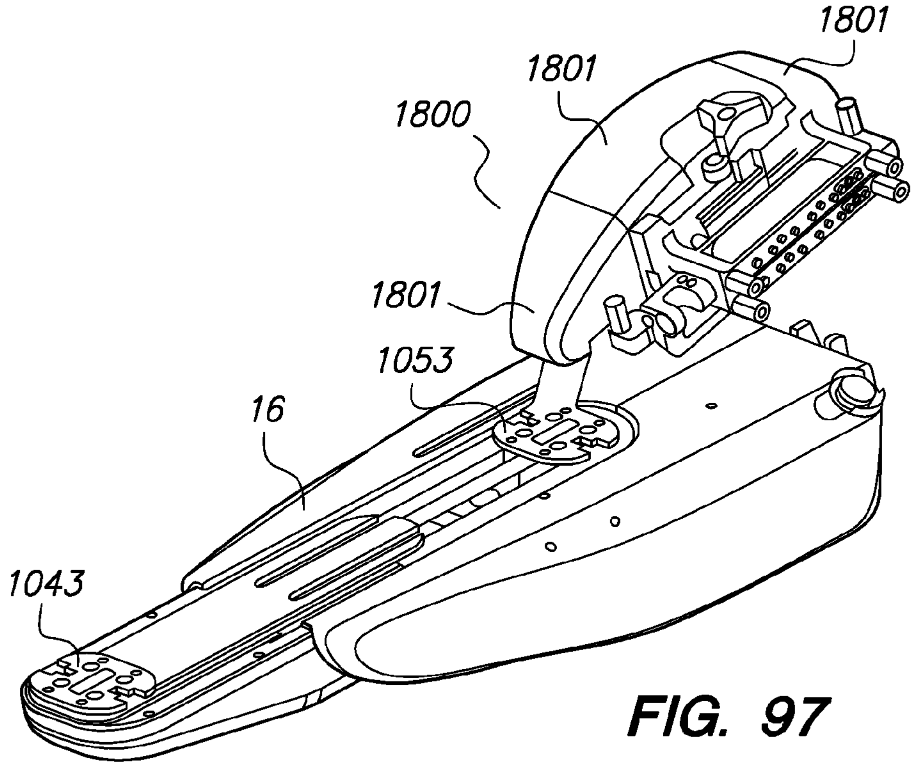


FIG. 97

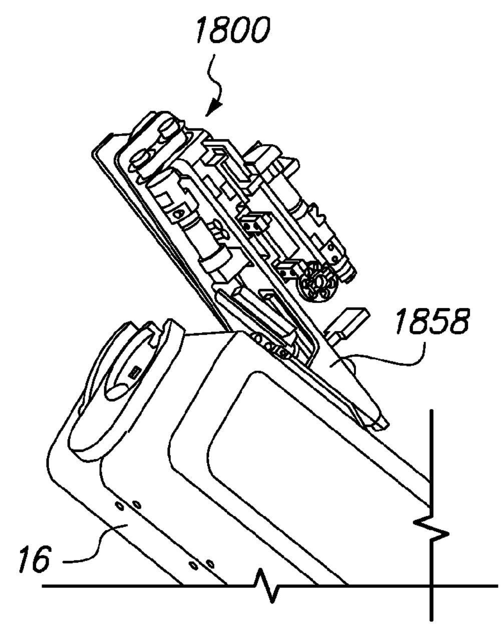


FIG. 97AA

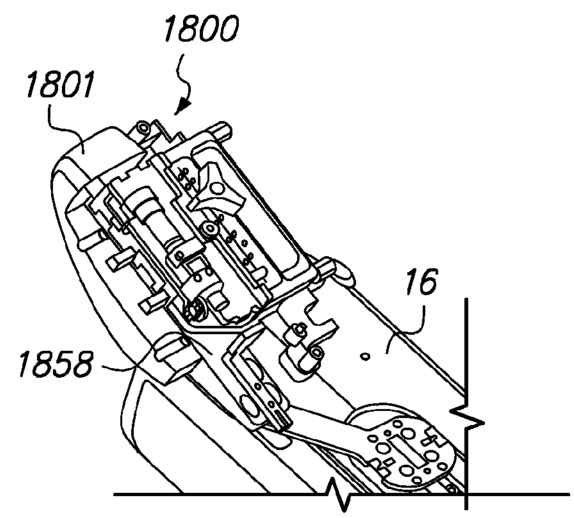


FIG. 97AB

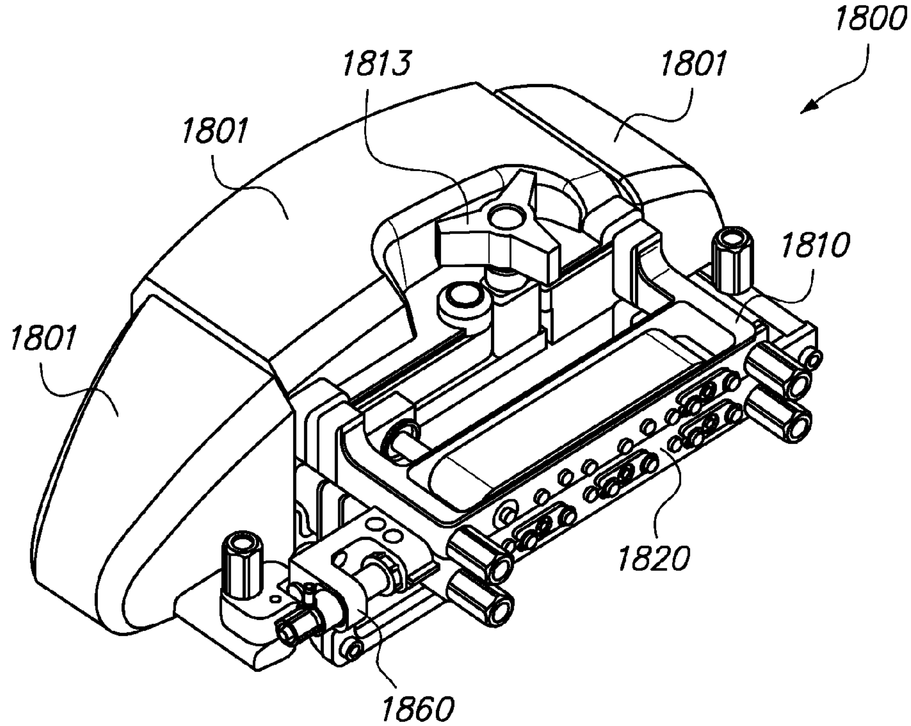


FIG. 97A1

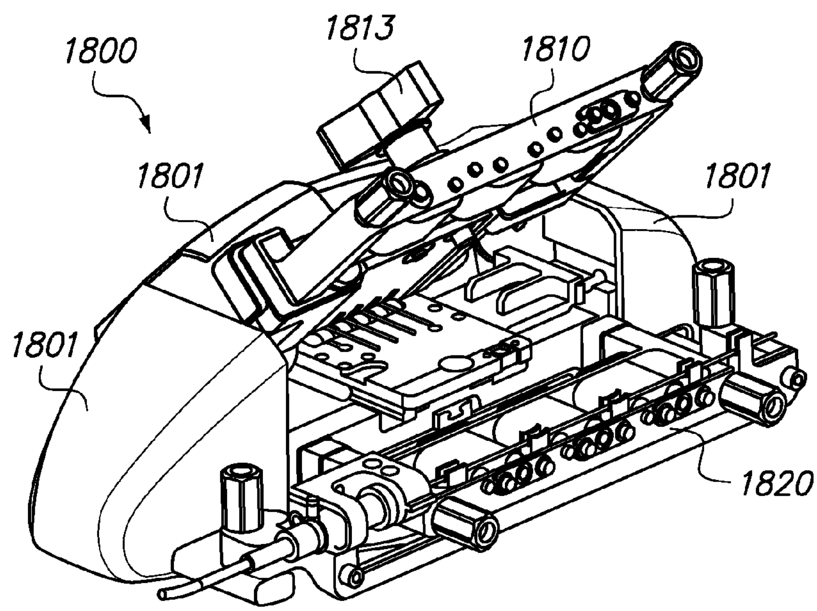


FIG. 97A2

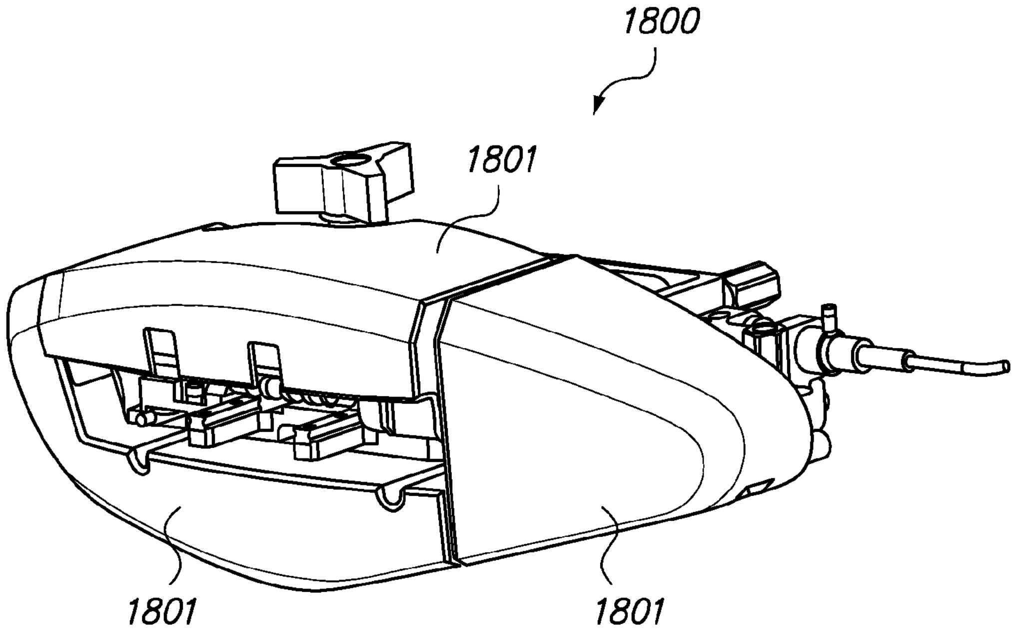


FIG. 97A3

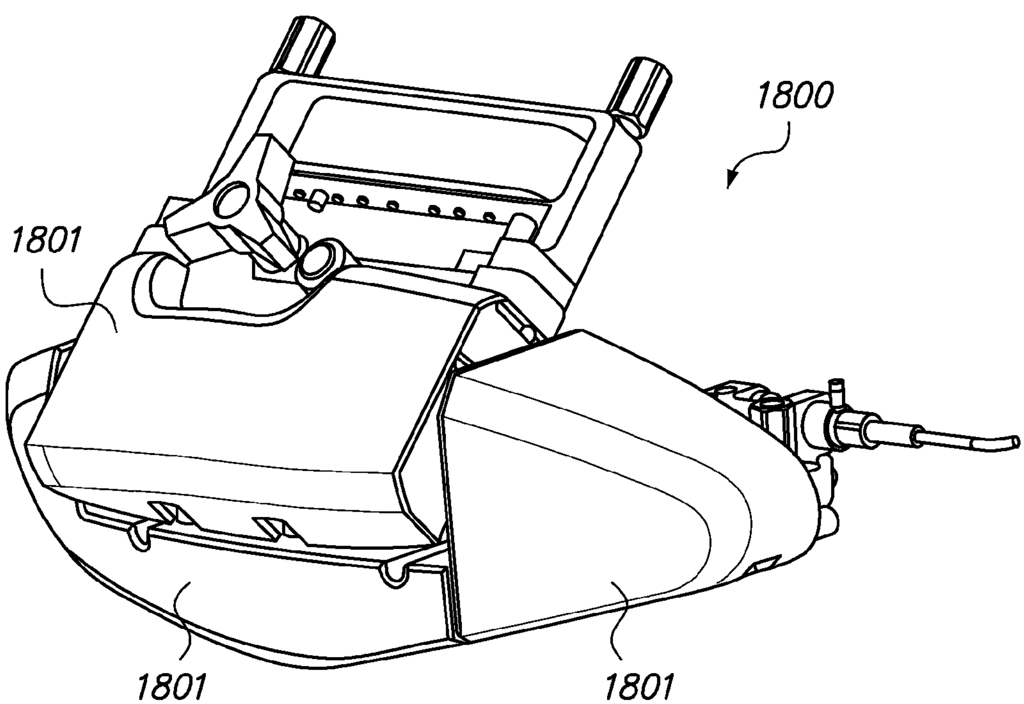


FIG. 97A4

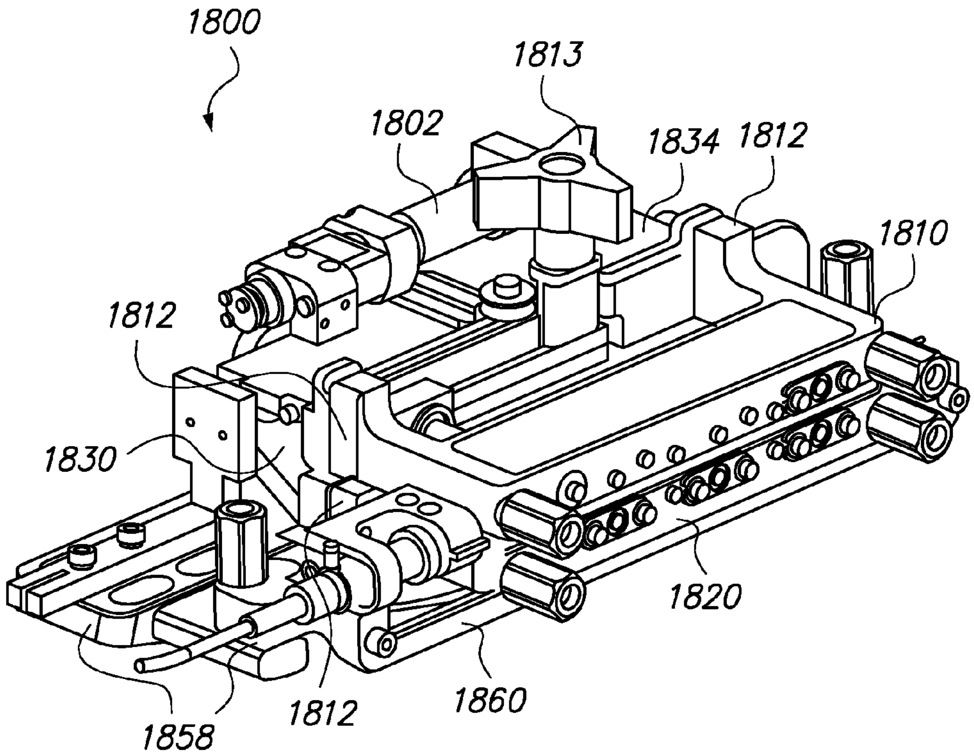


FIG. 97B1

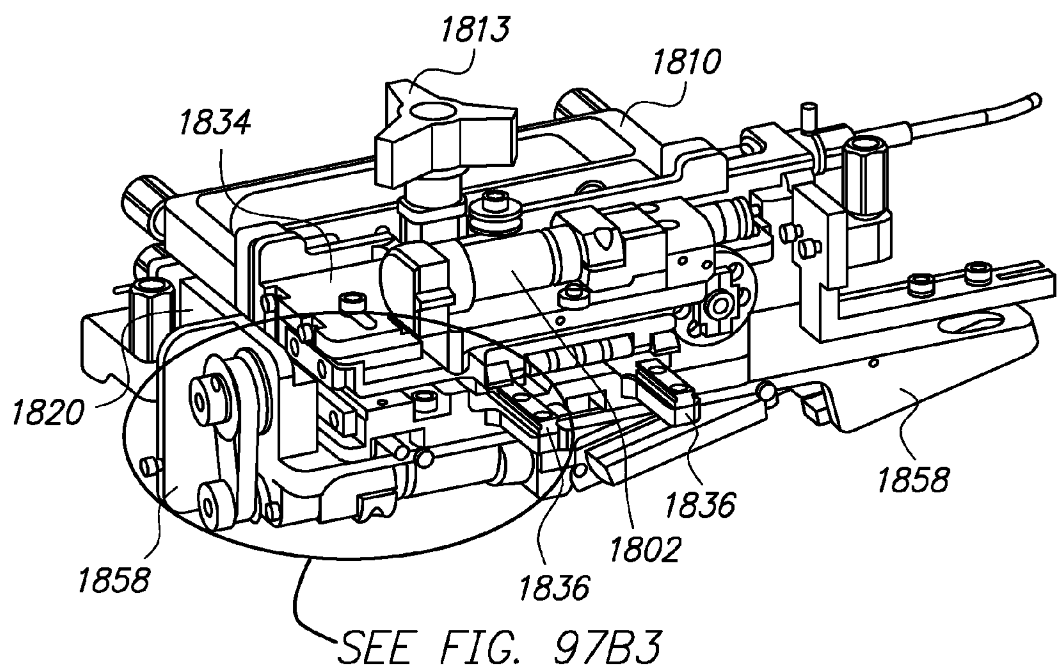


FIG. 97B2

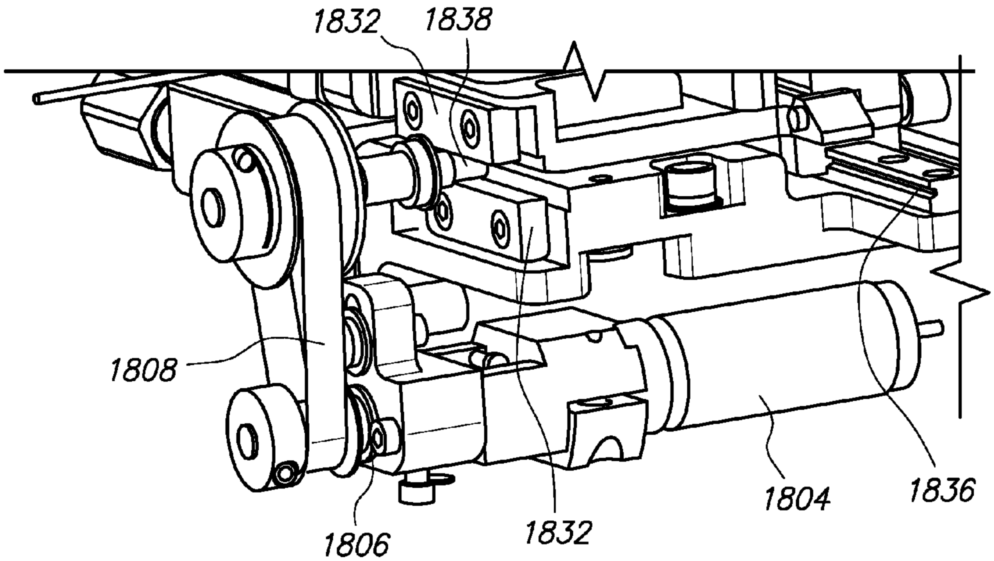


FIG. 97B3

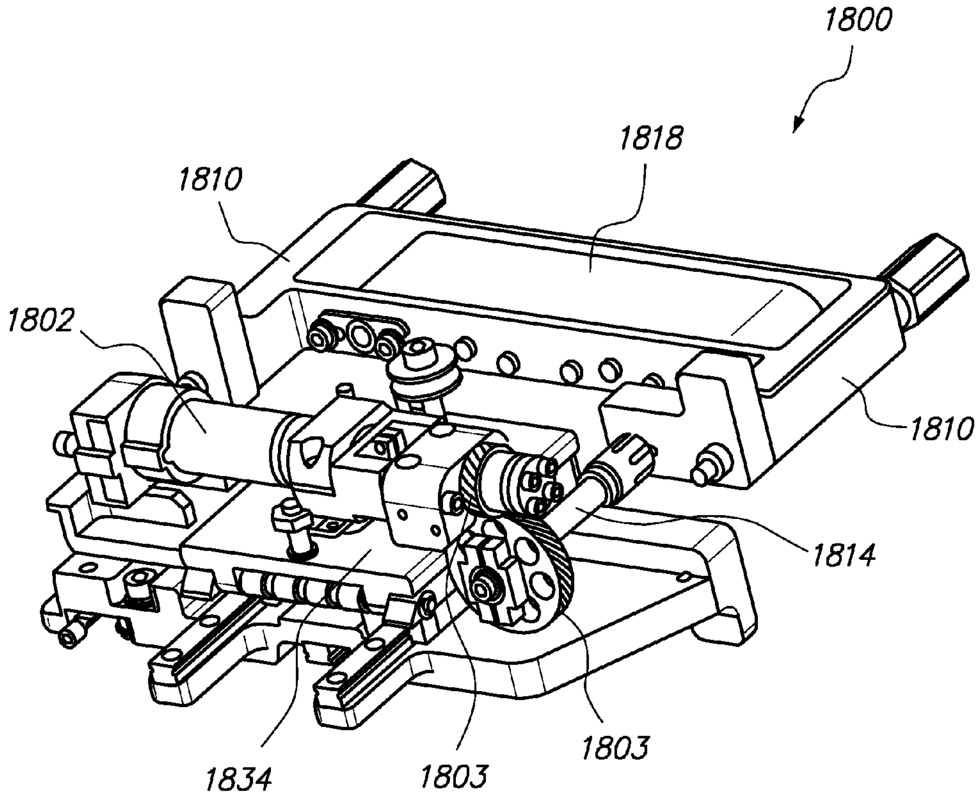


FIG. 97C

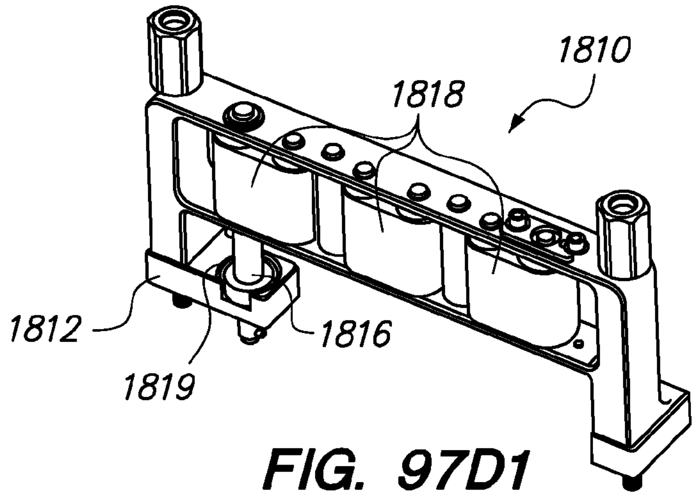


FIG. 97D1

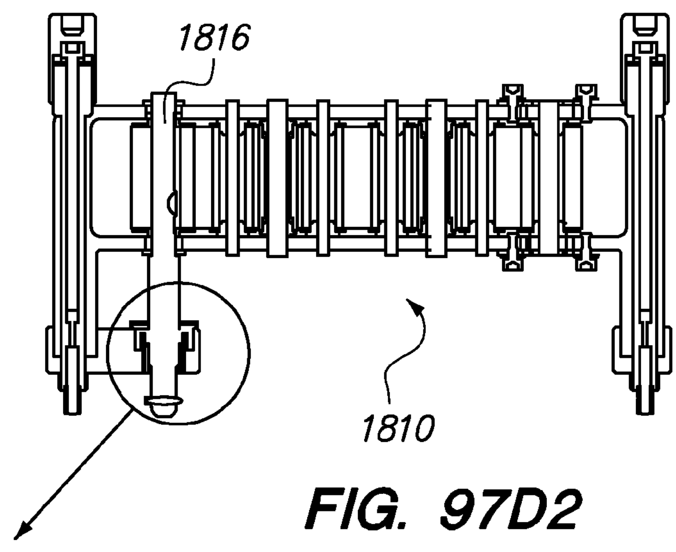


FIG. 97D2

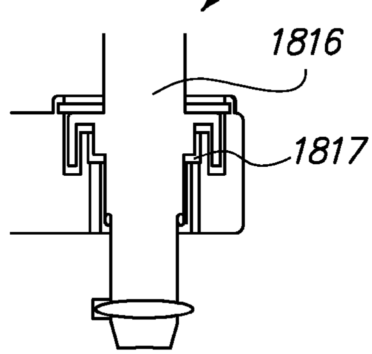


FIG. 97D3

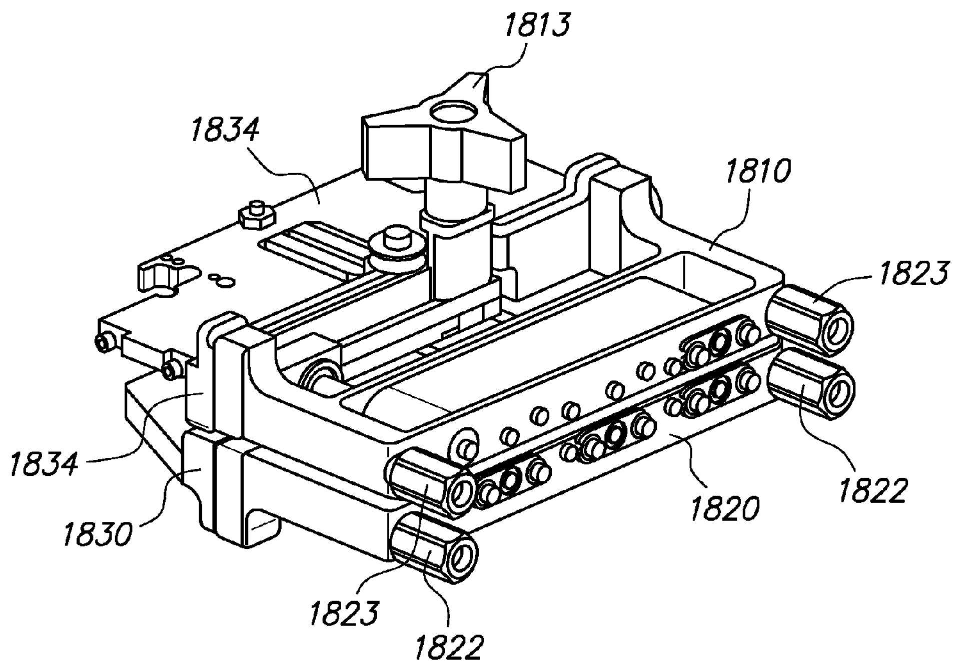


FIG. 97E1

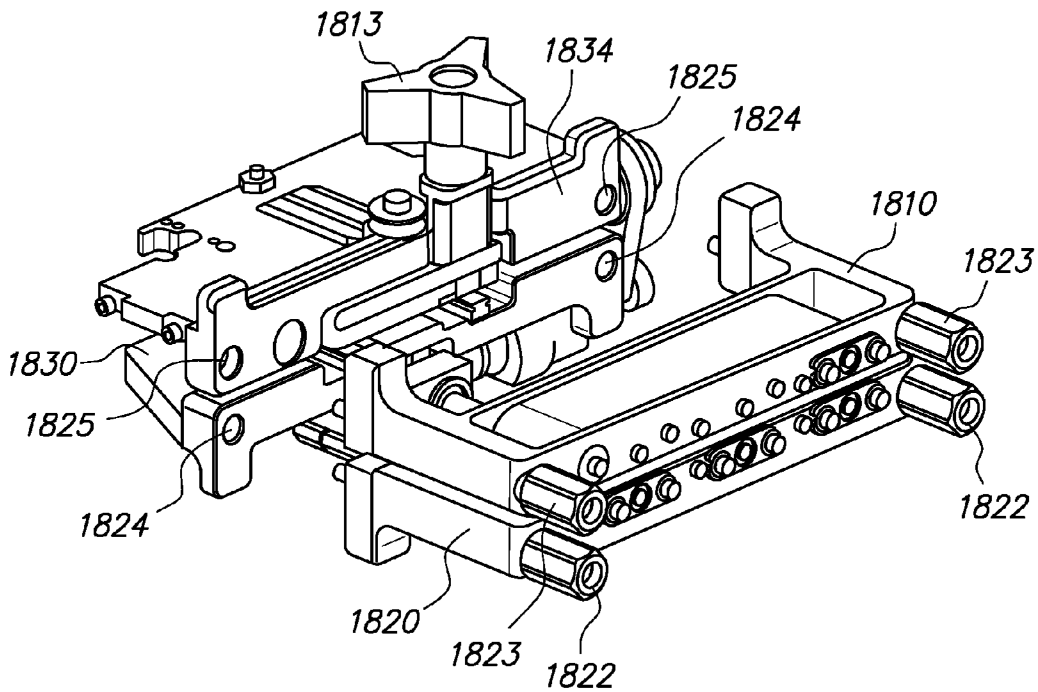


FIG. 97E2

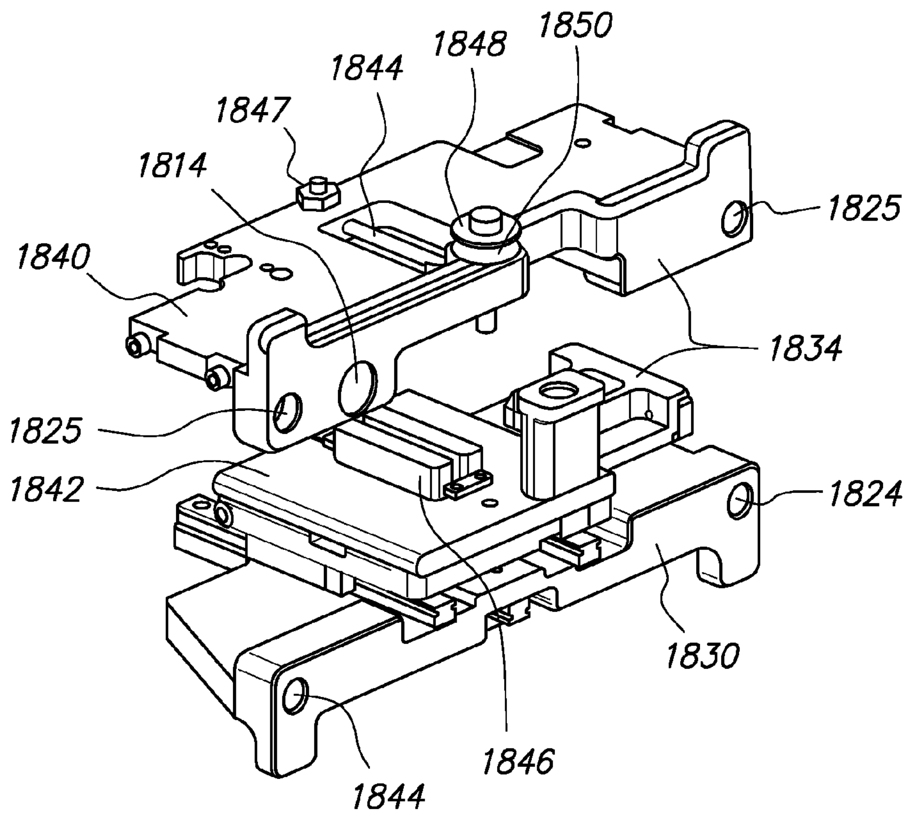


FIG. 97F

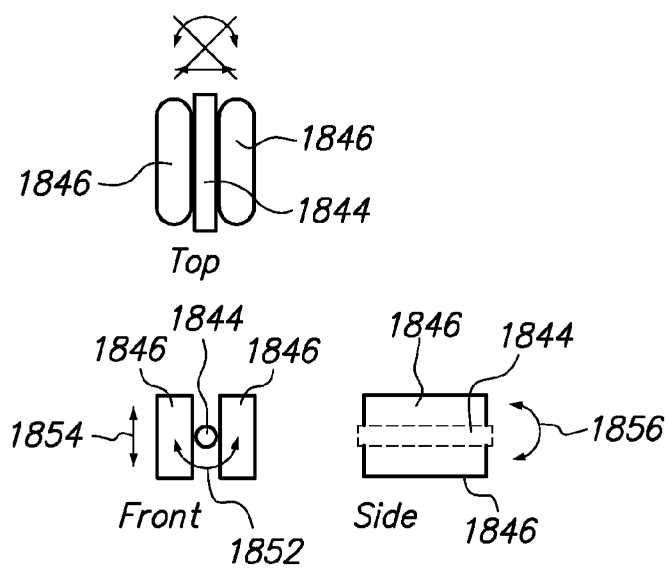


FIG. 97G

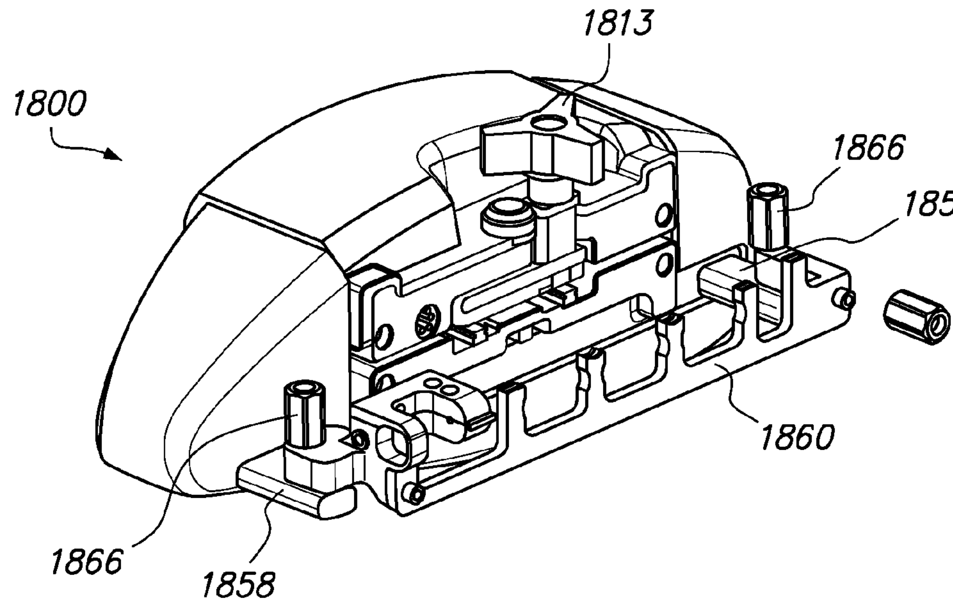


FIG. 97H1

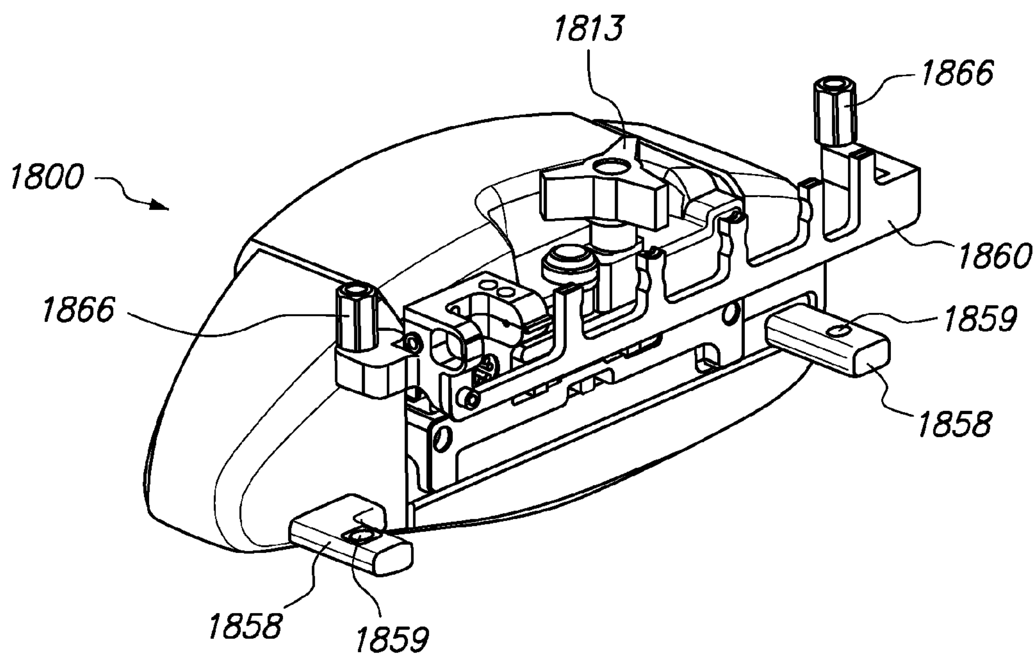


FIG. 97H2

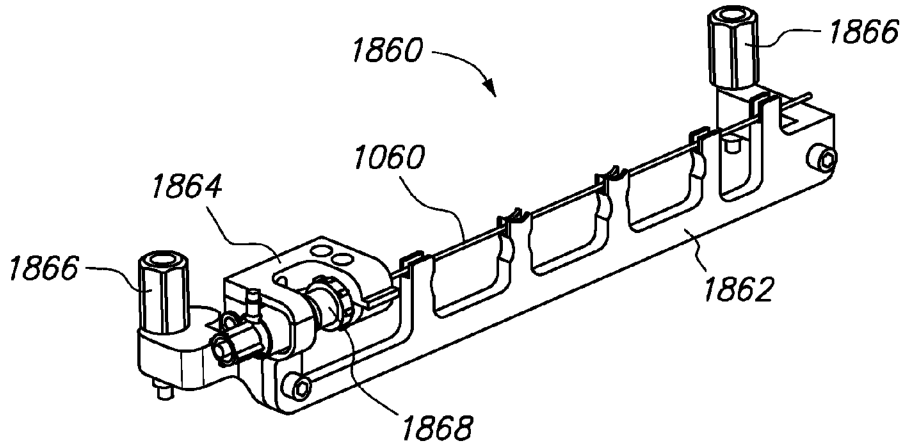


FIG. 97J1

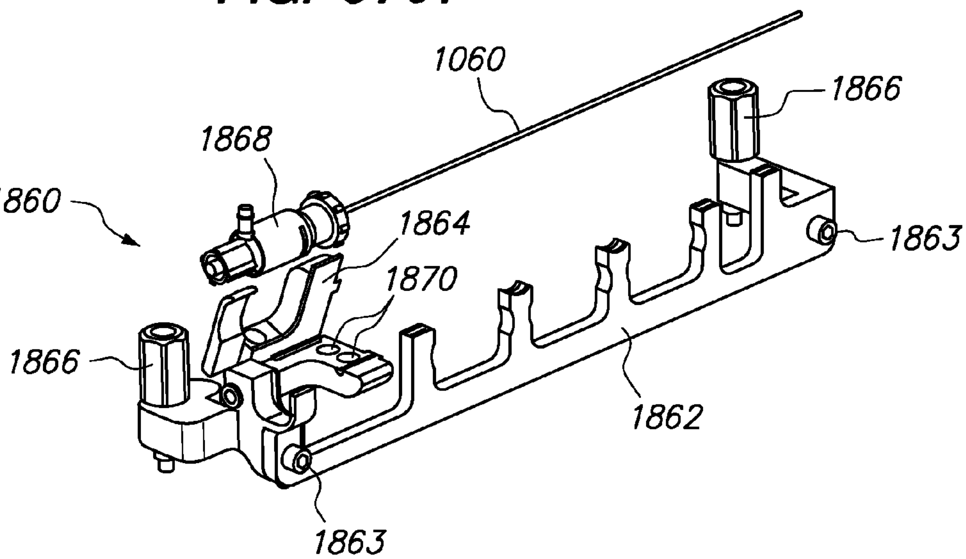


FIG. 97J2

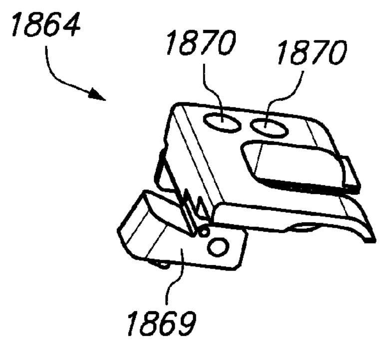


FIG. 97J3

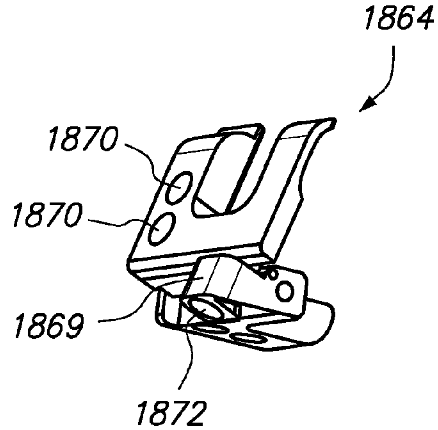


FIG. 97J4

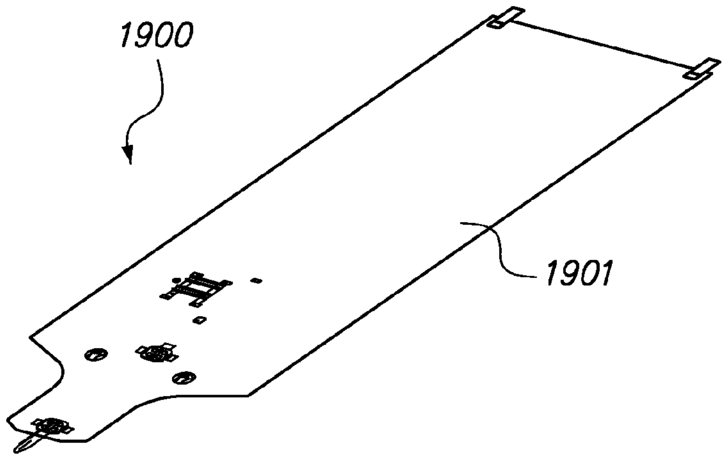


FIG. 97K1

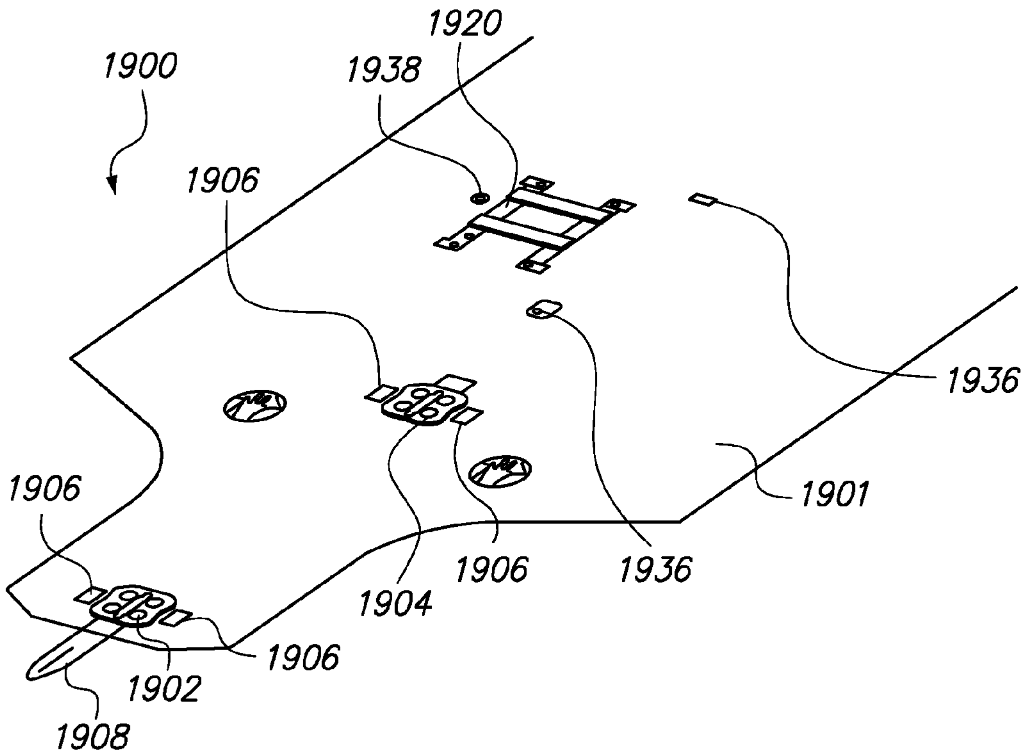


FIG. 97K2

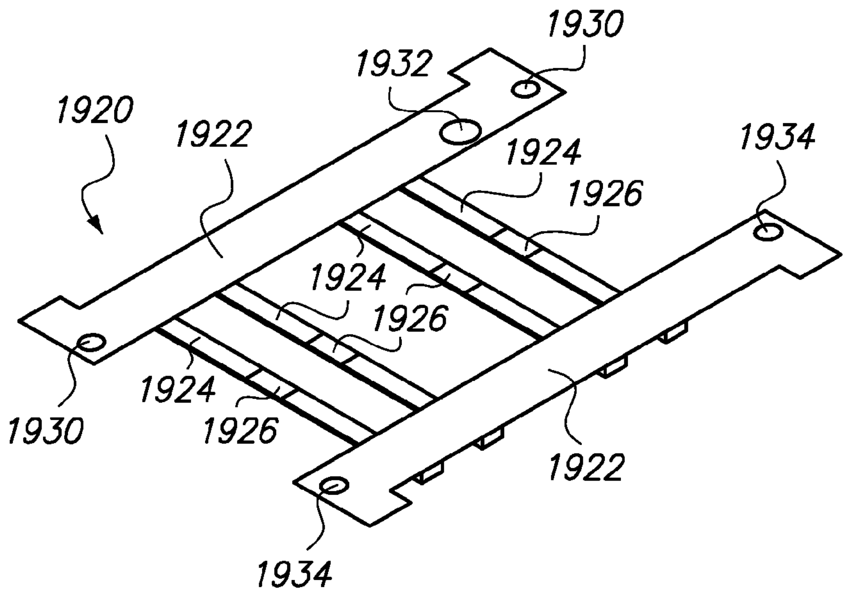


FIG. 97L1

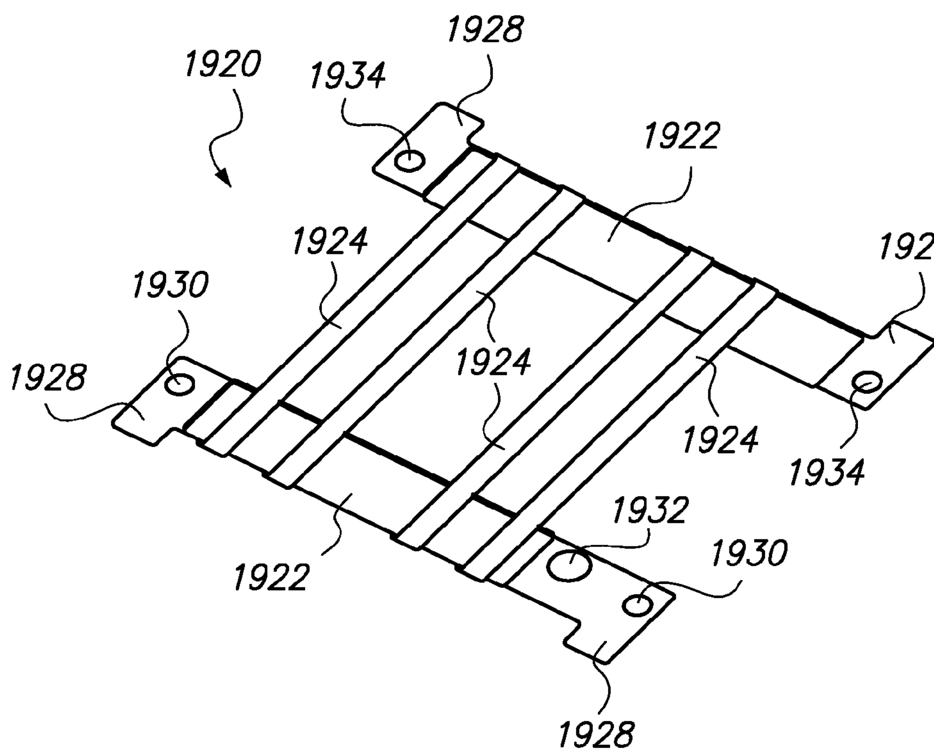


FIG. 97L2

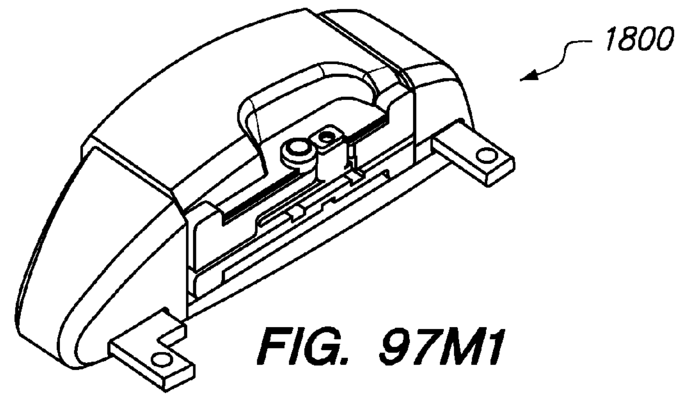


FIG. 97M1

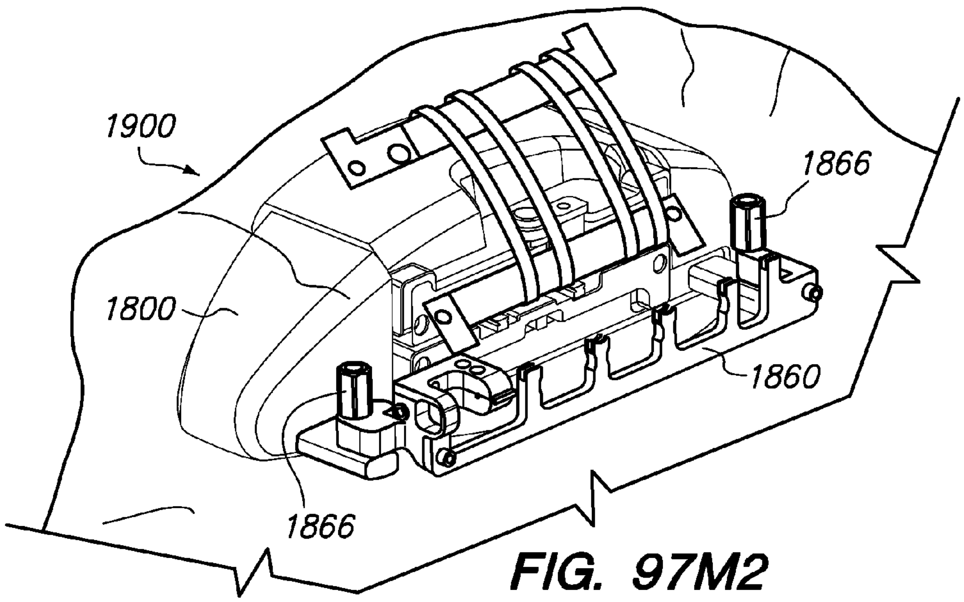


FIG. 97M2

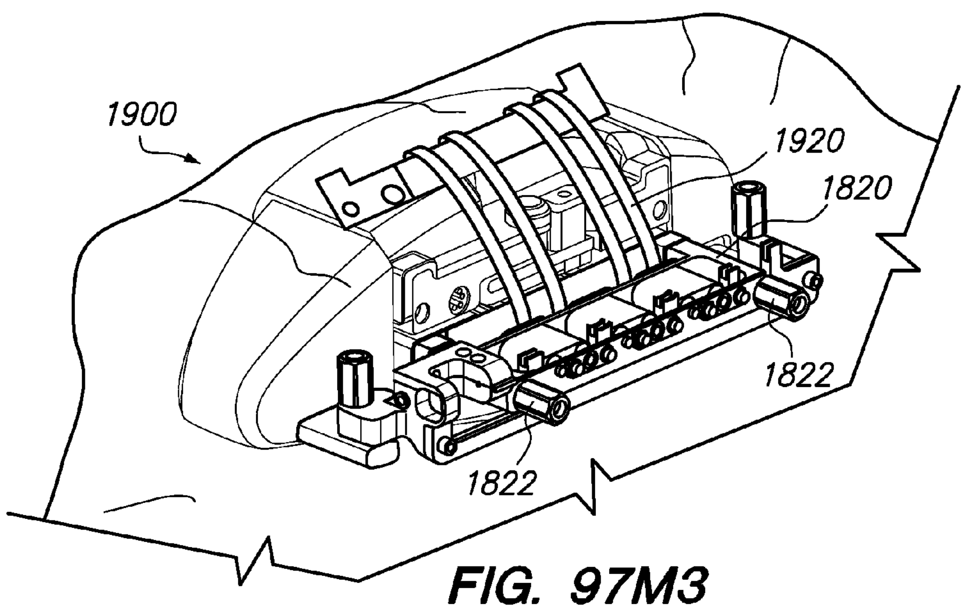


FIG. 97M3

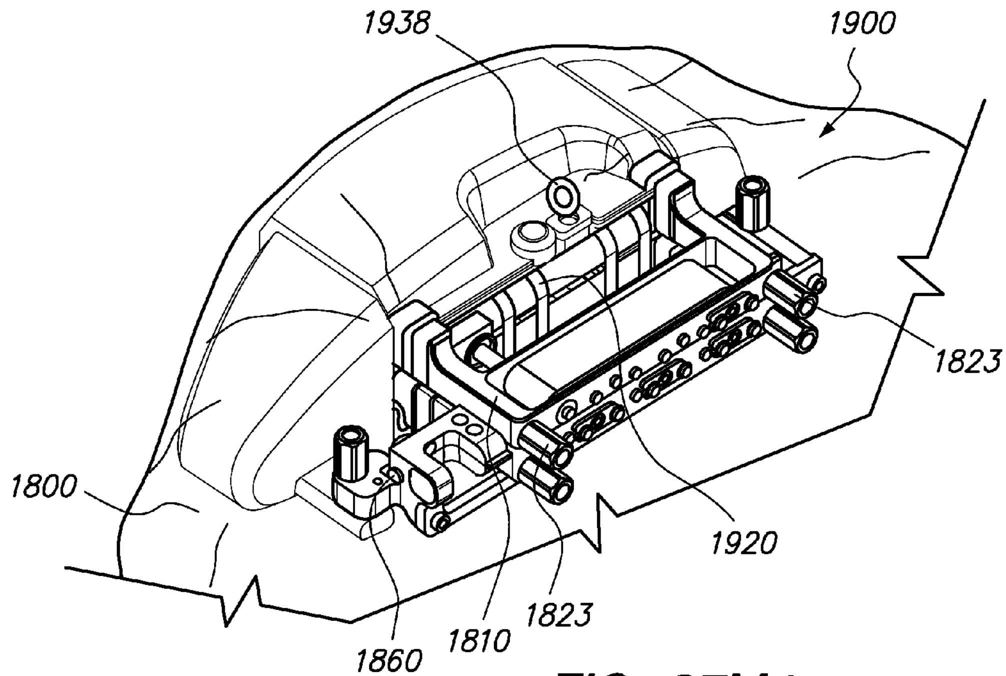


FIG. 97M4

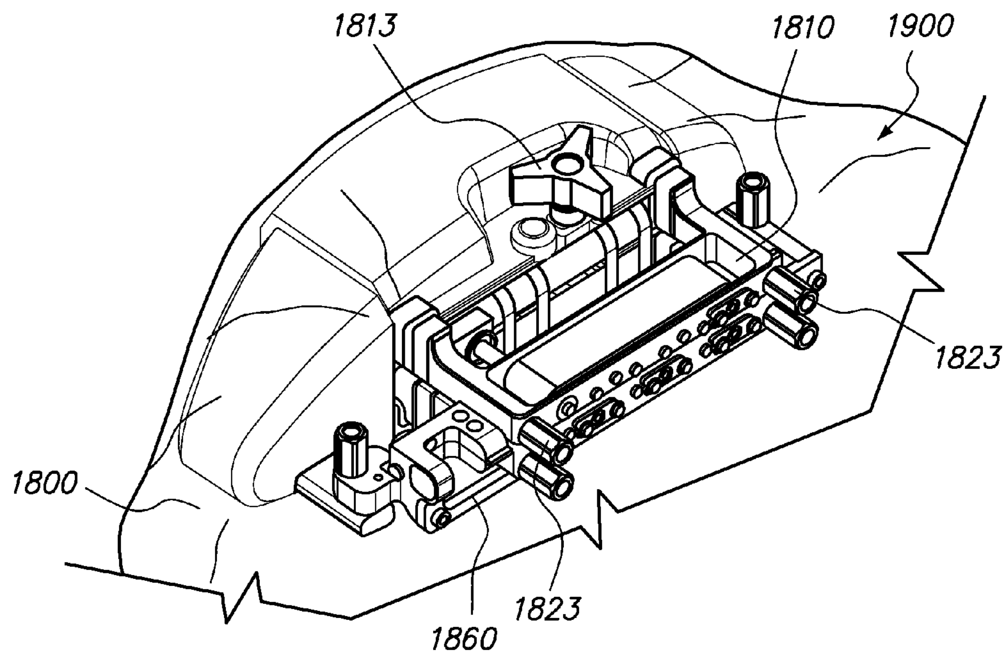


FIG. 97M5

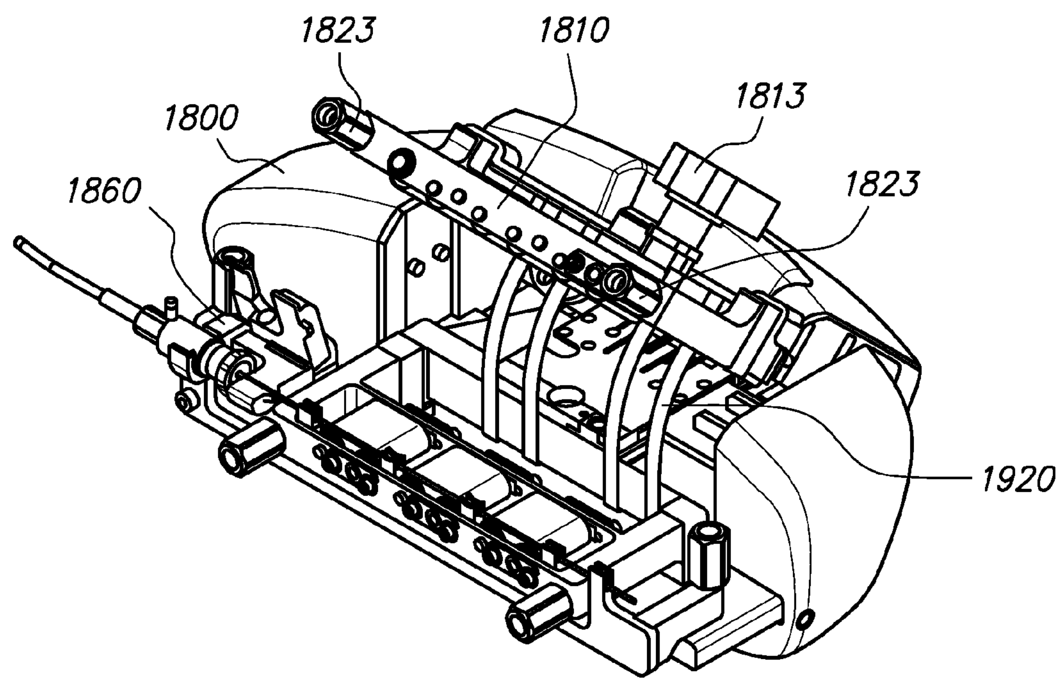


FIG. 97M6

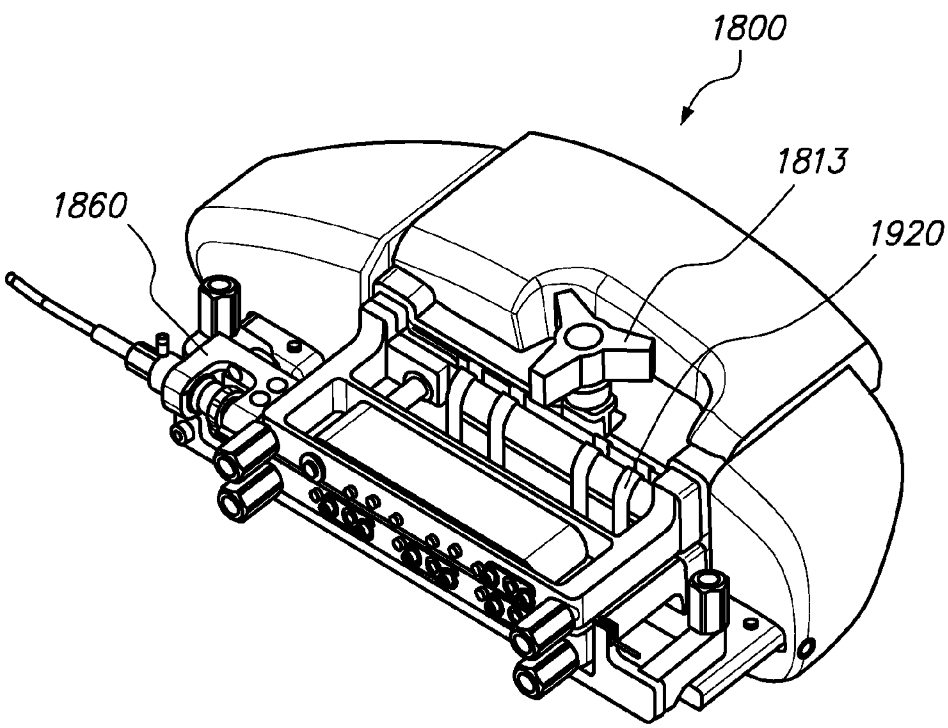


FIG. 97M7

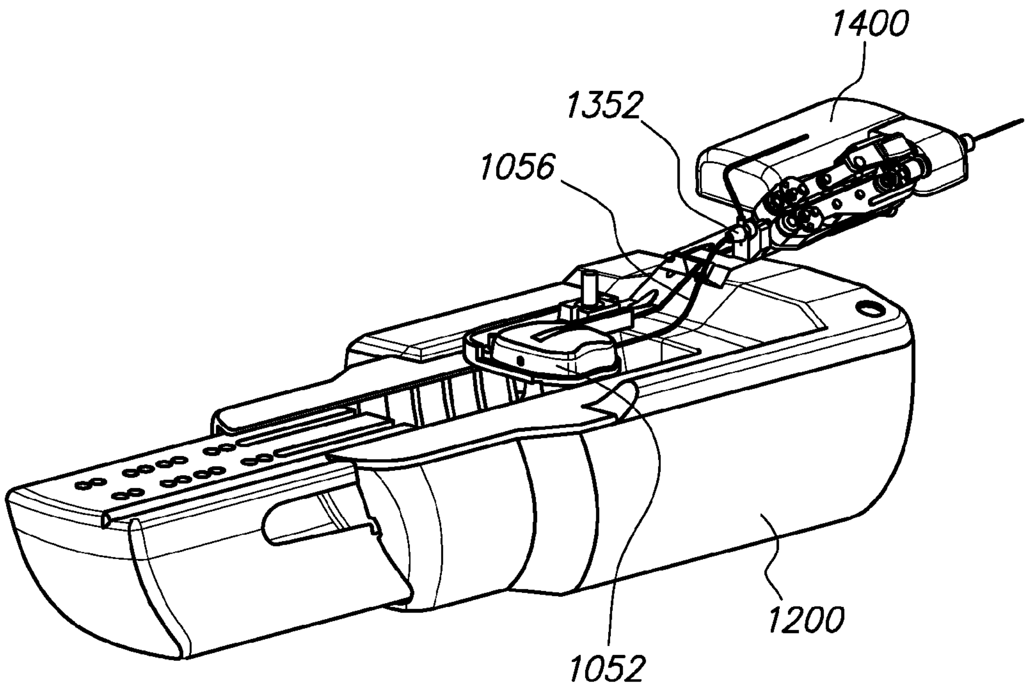


FIG. 98A

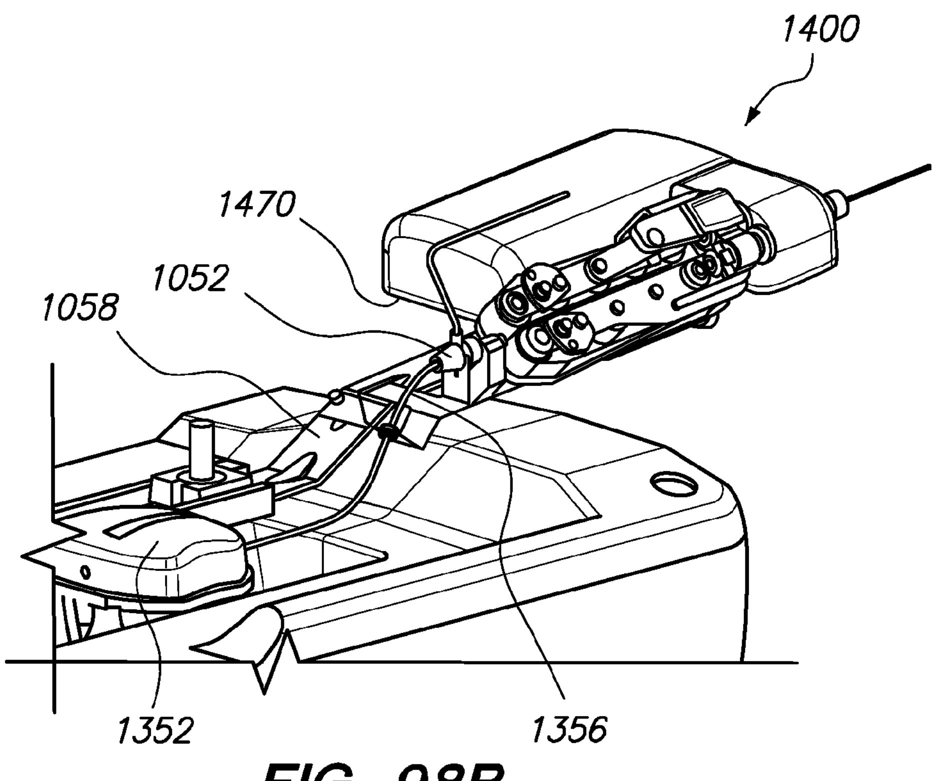


FIG. 98B

FIG. 99

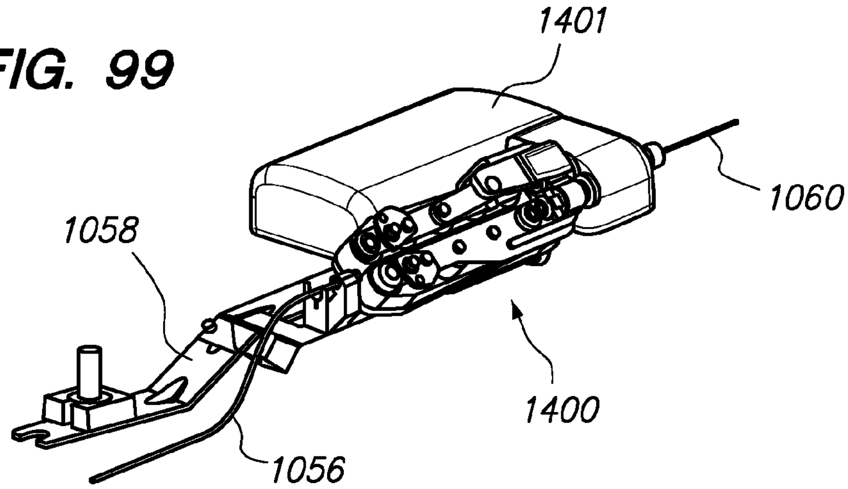


FIG. 100A

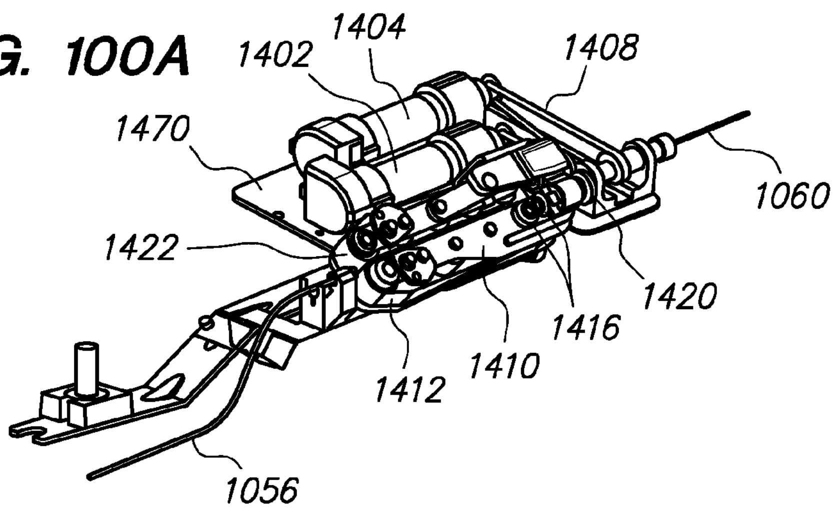


FIG. 100B

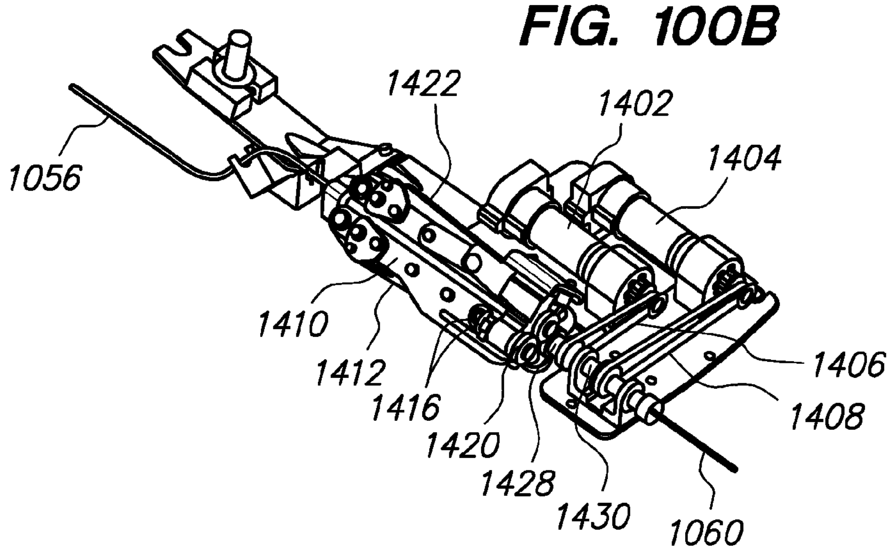
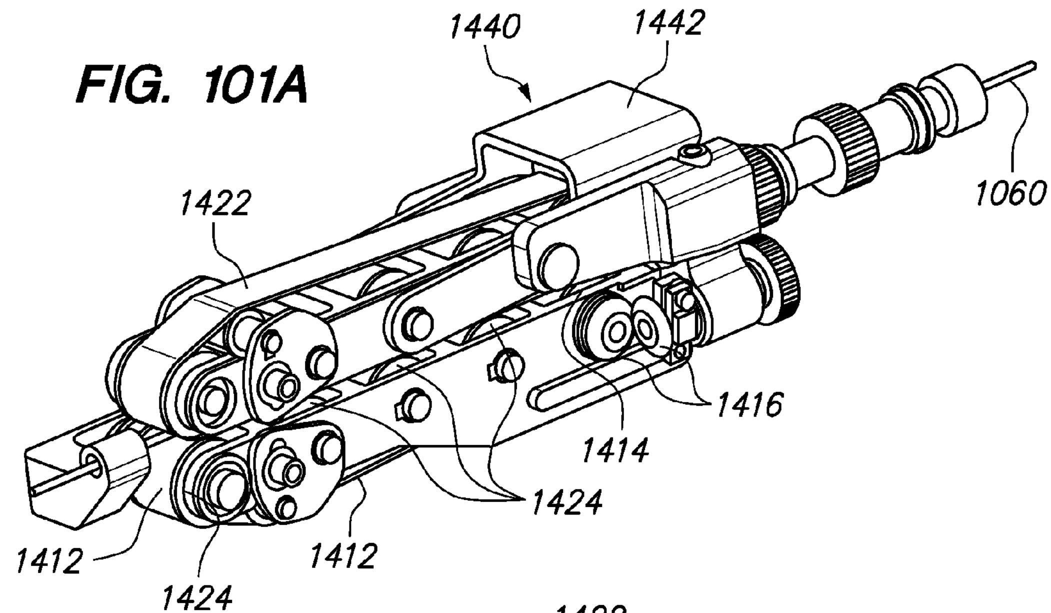


FIG. 101A



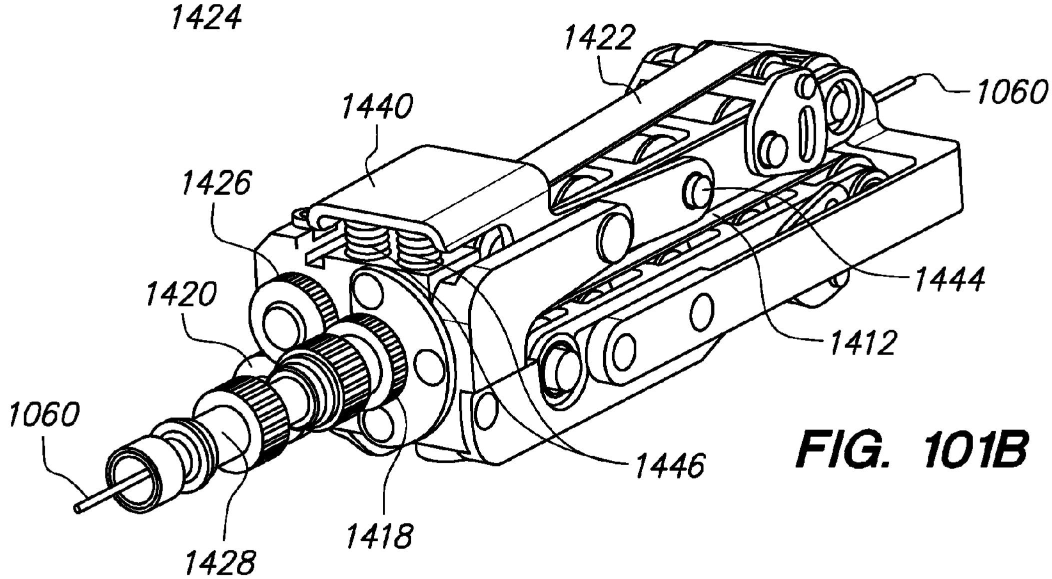
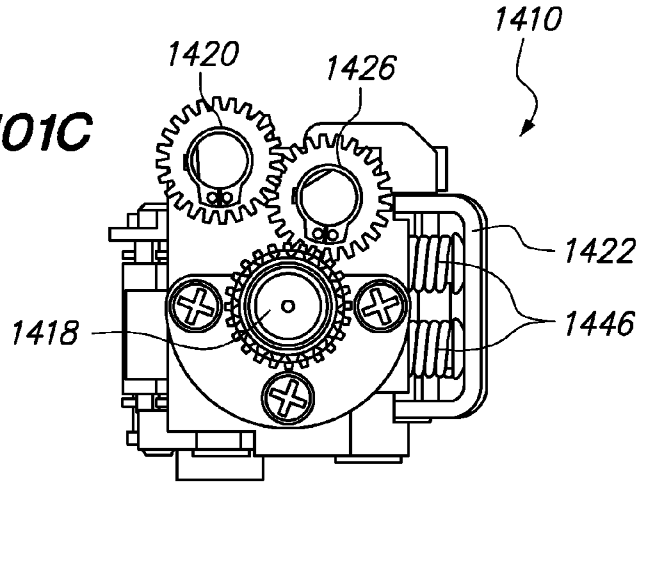


FIG. 101B

FIG. 101C



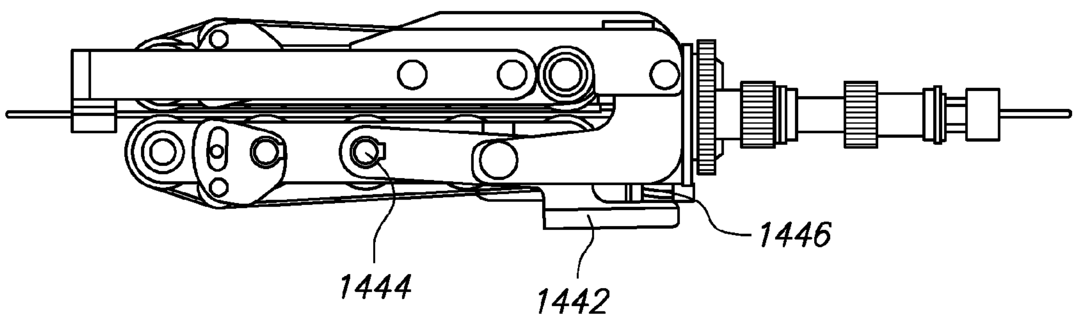


FIG. 102A

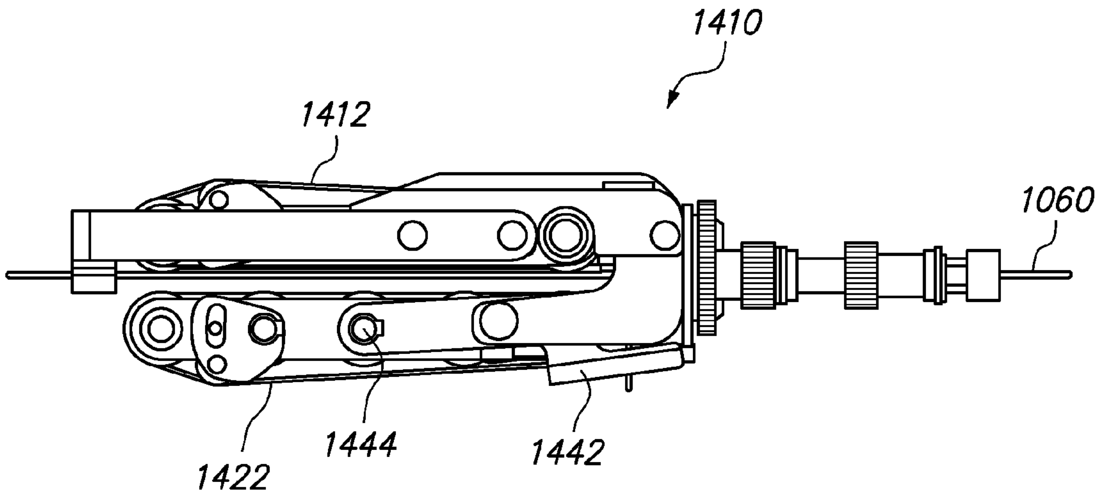


FIG. 102B

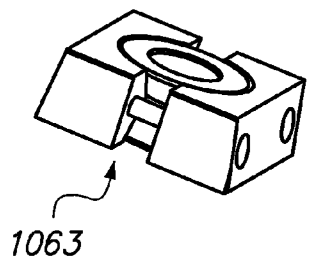


FIG. 103AA

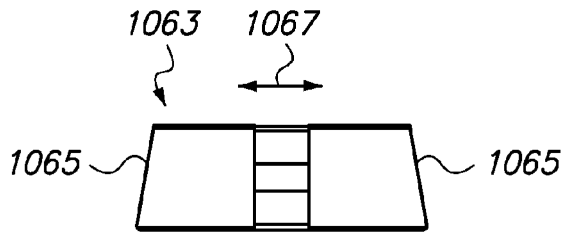


FIG. 103AB

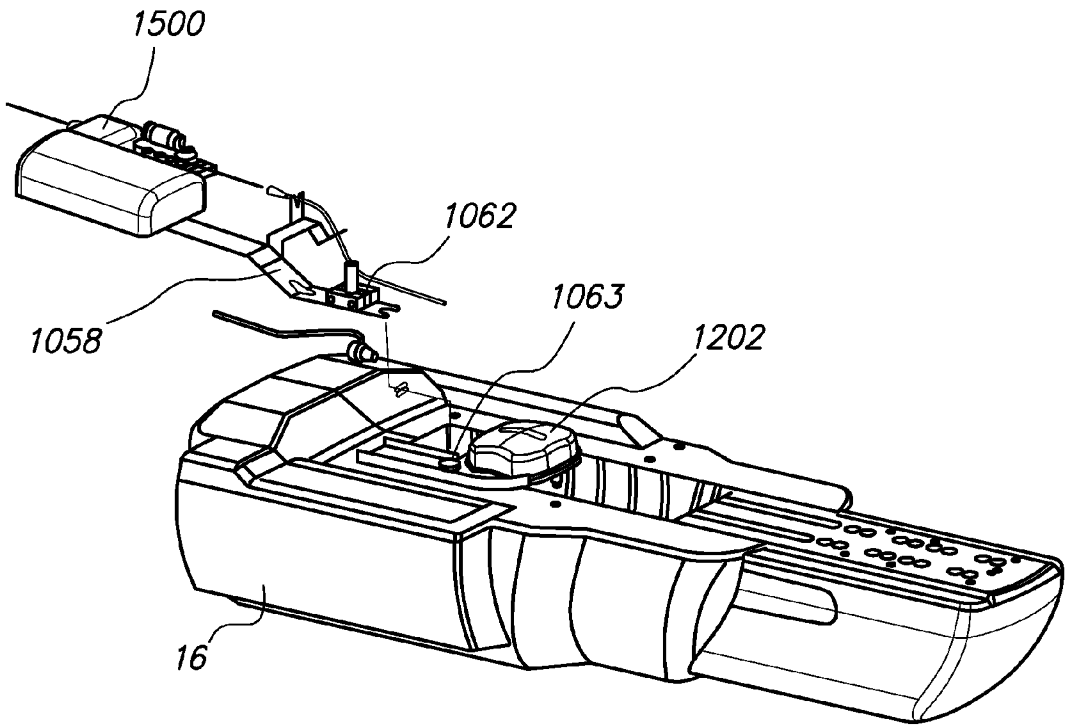


FIG. 103

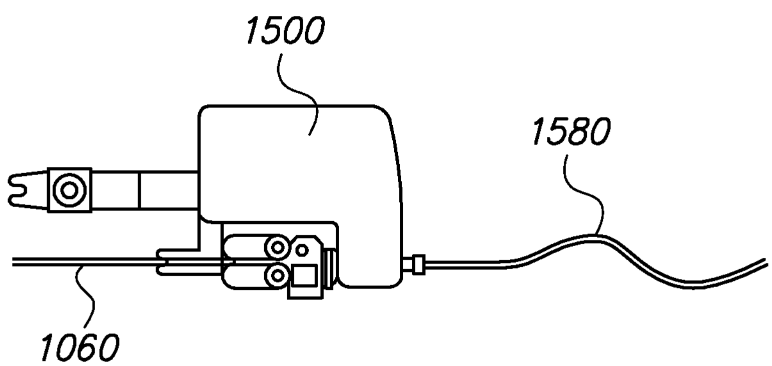


FIG. 103A

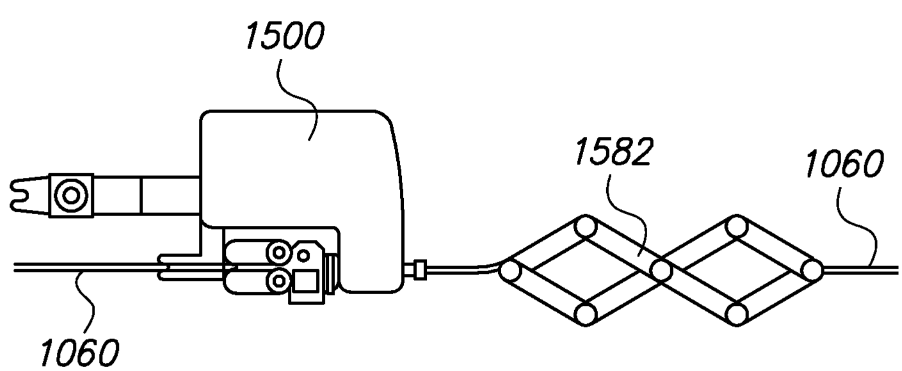


FIG. 103B

FIG. 104

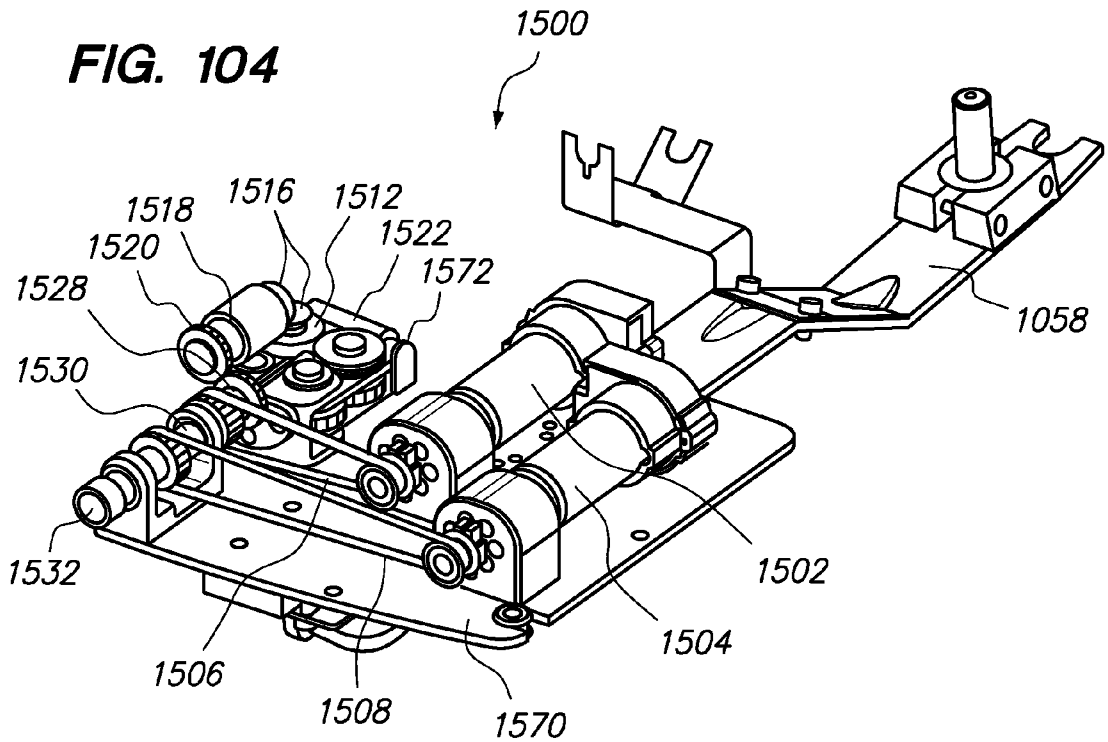


FIG. 105

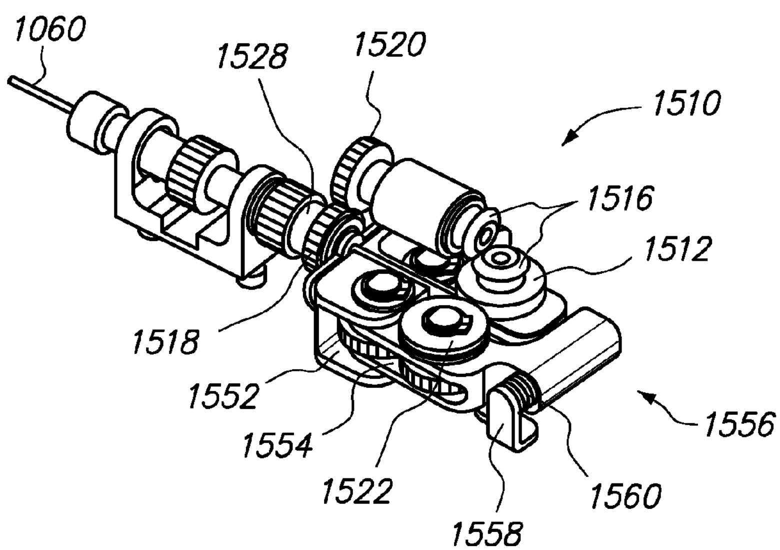


FIG. 106A

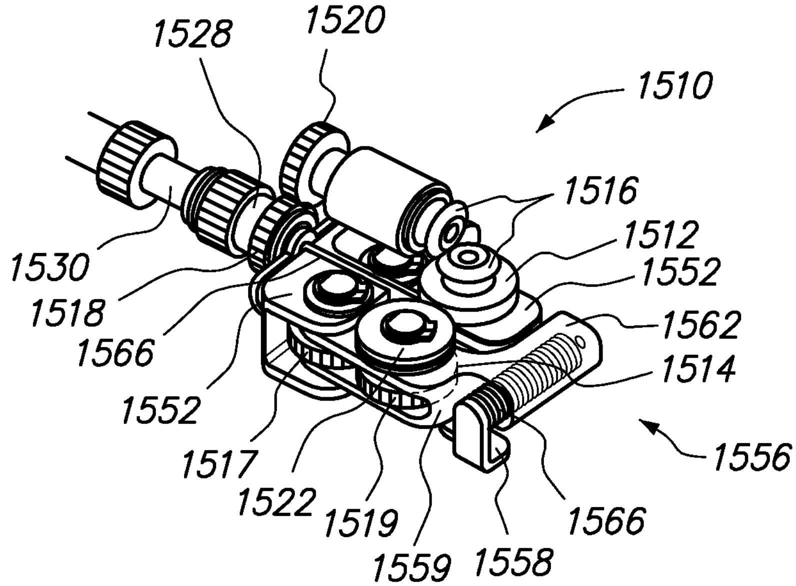


FIG. 106B

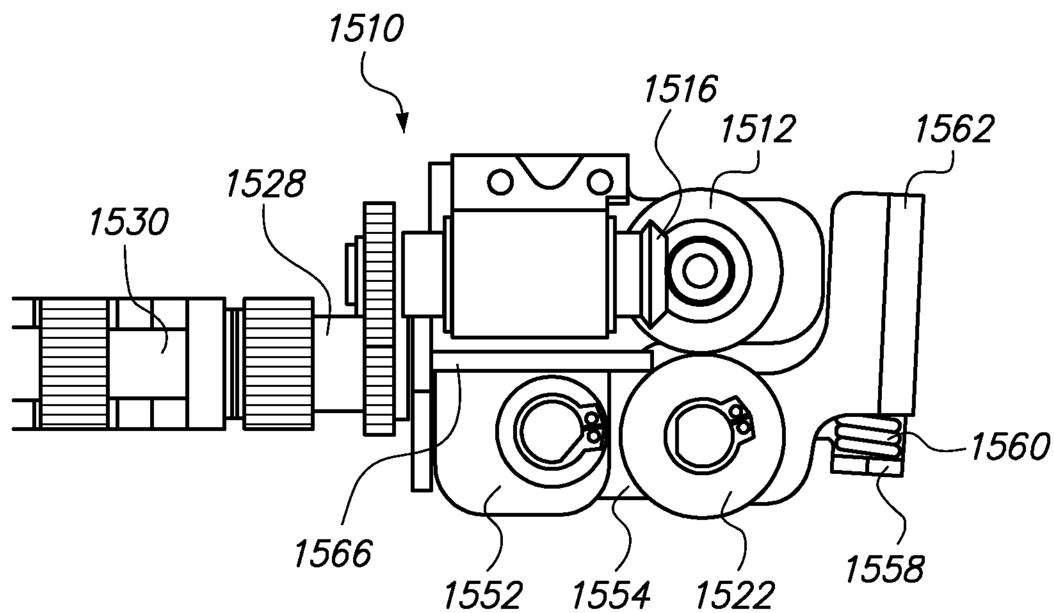


FIG. 107A

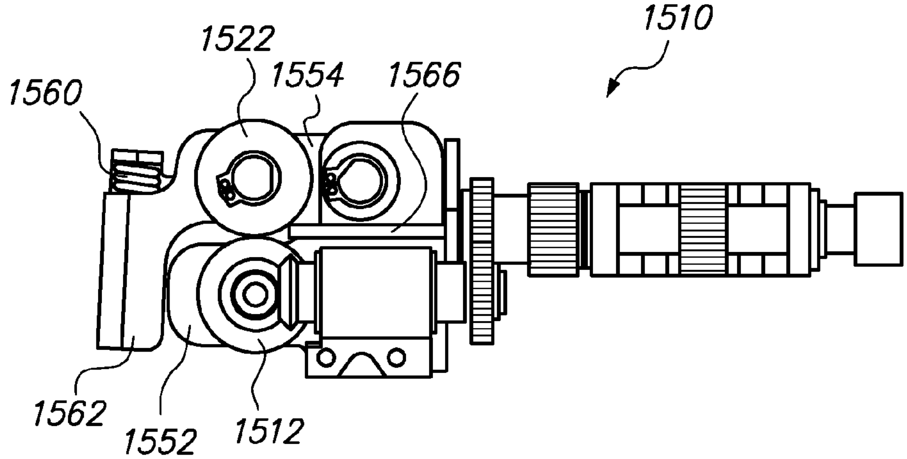
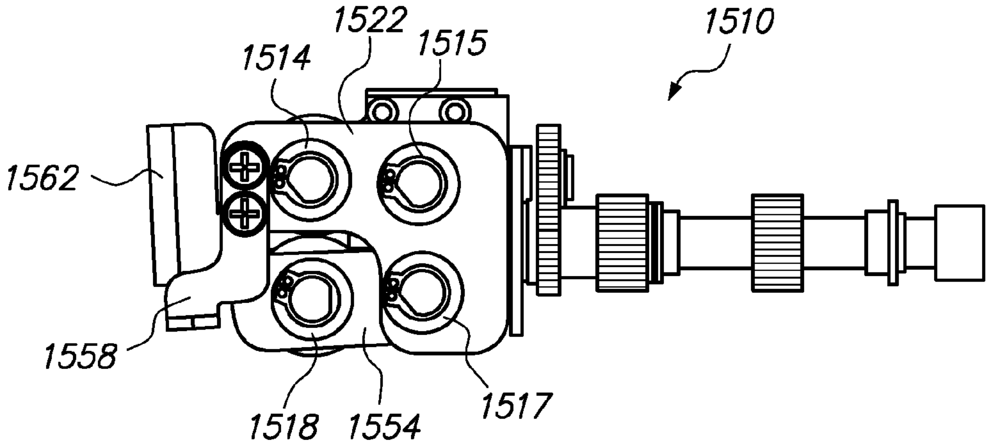


FIG. 107B



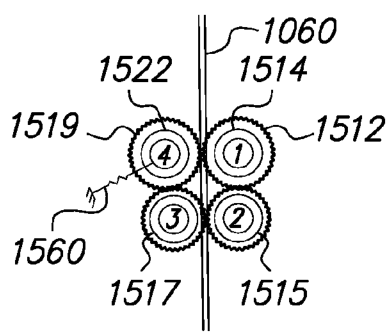


FIG. 108A

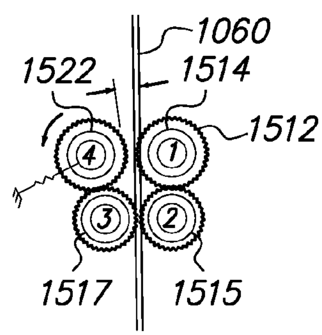


FIG. 108B

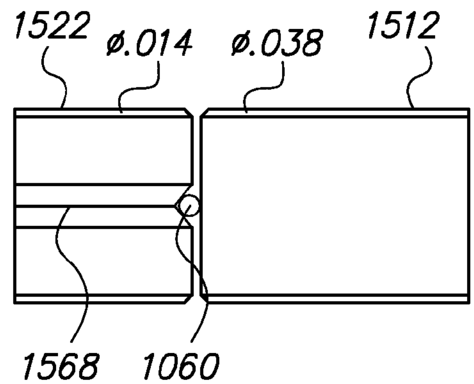


FIG. 109

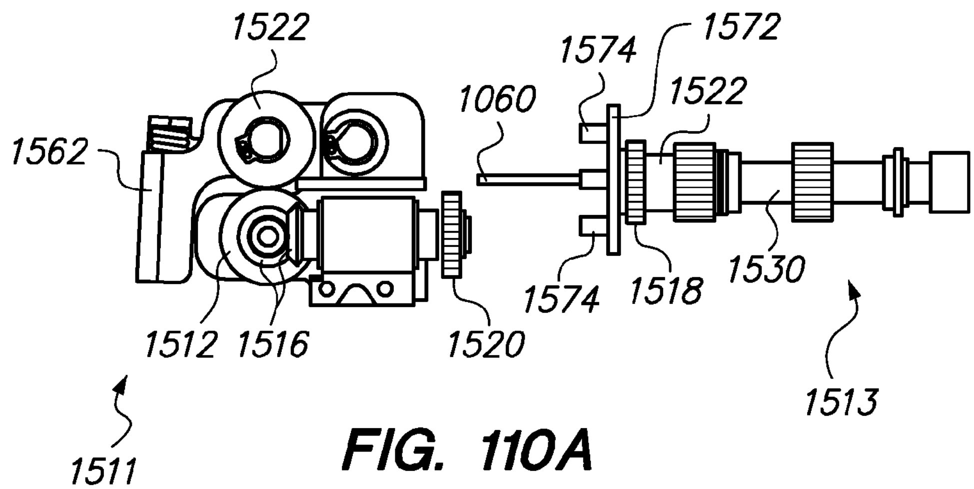


FIG. 110A

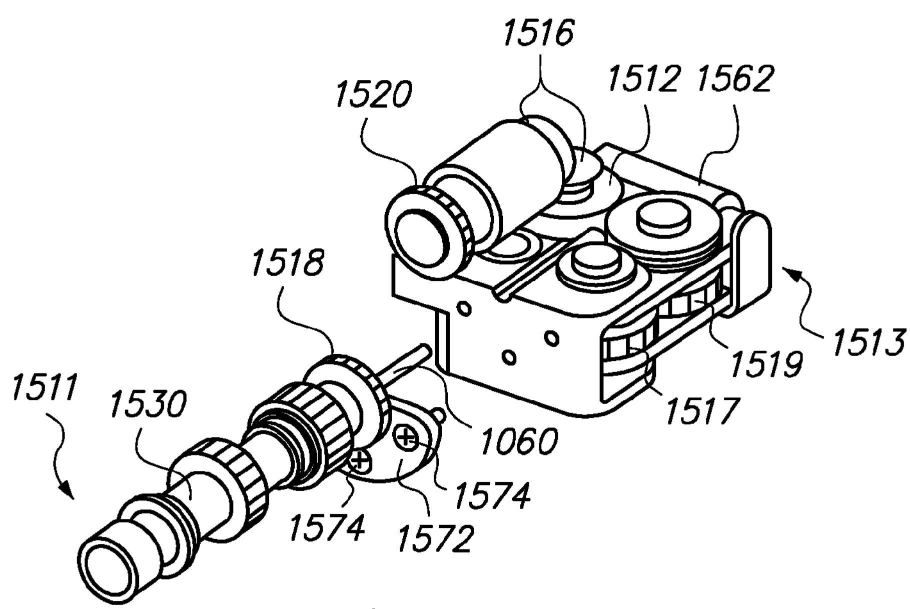


FIG. 110B

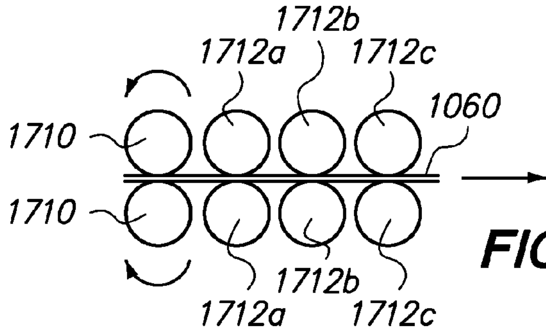


FIG. 111A

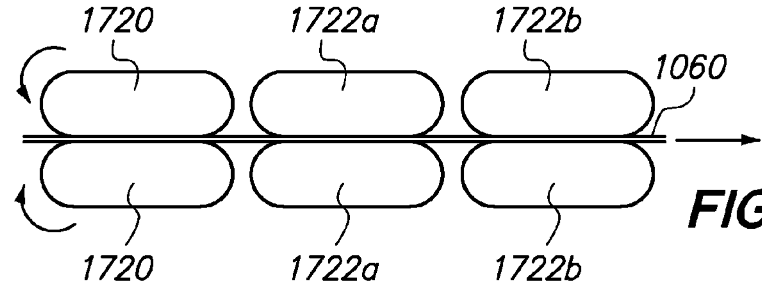


FIG. 111B

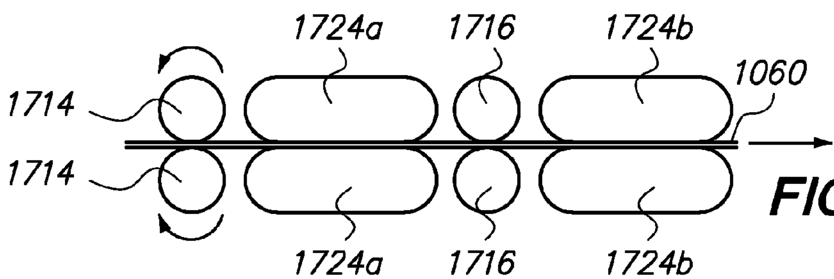


FIG. 111C

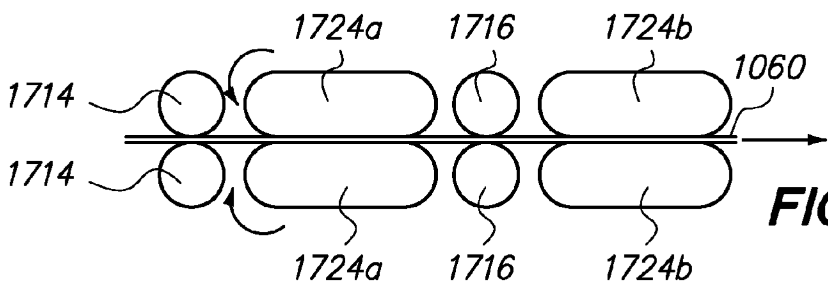


FIG. 111D

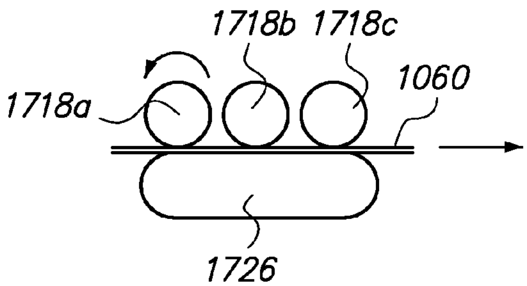


FIG. 111E

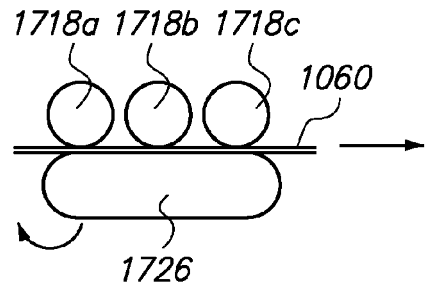


FIG. 111F

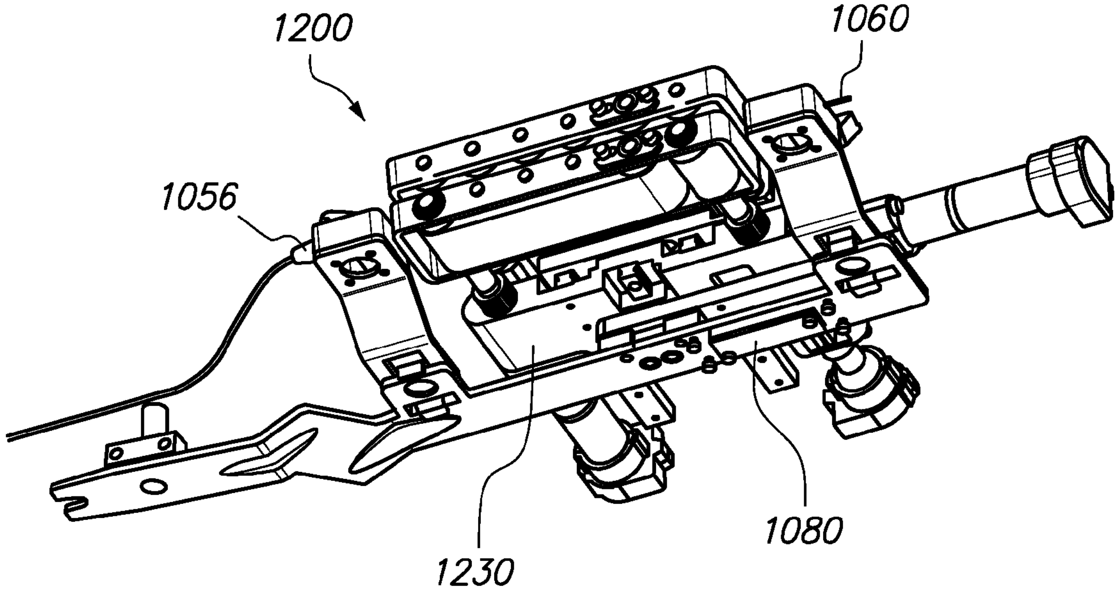


FIG. 112A

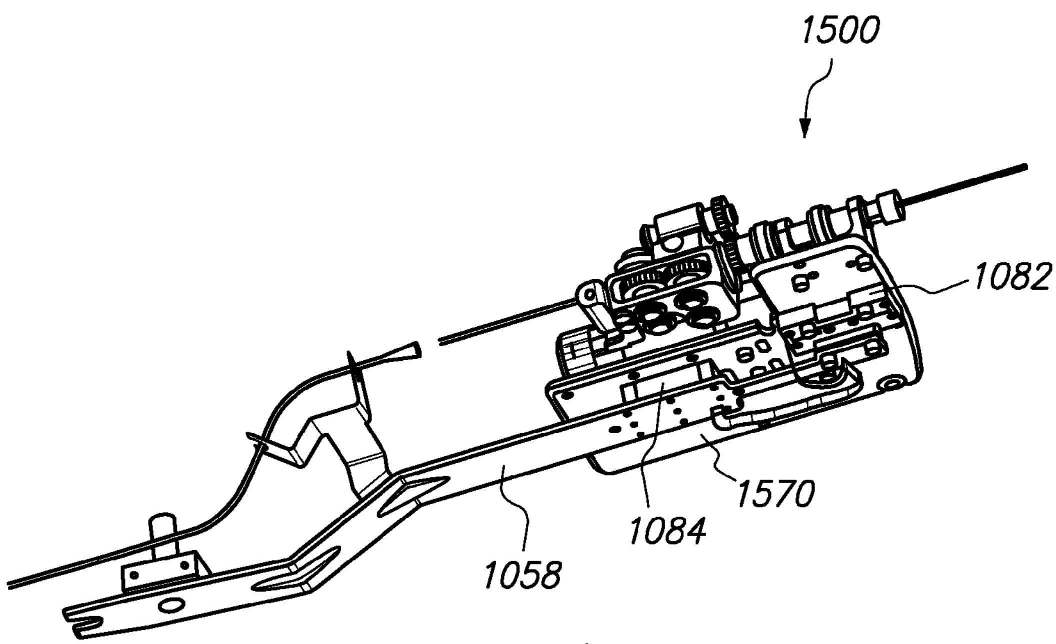


FIG. 112B

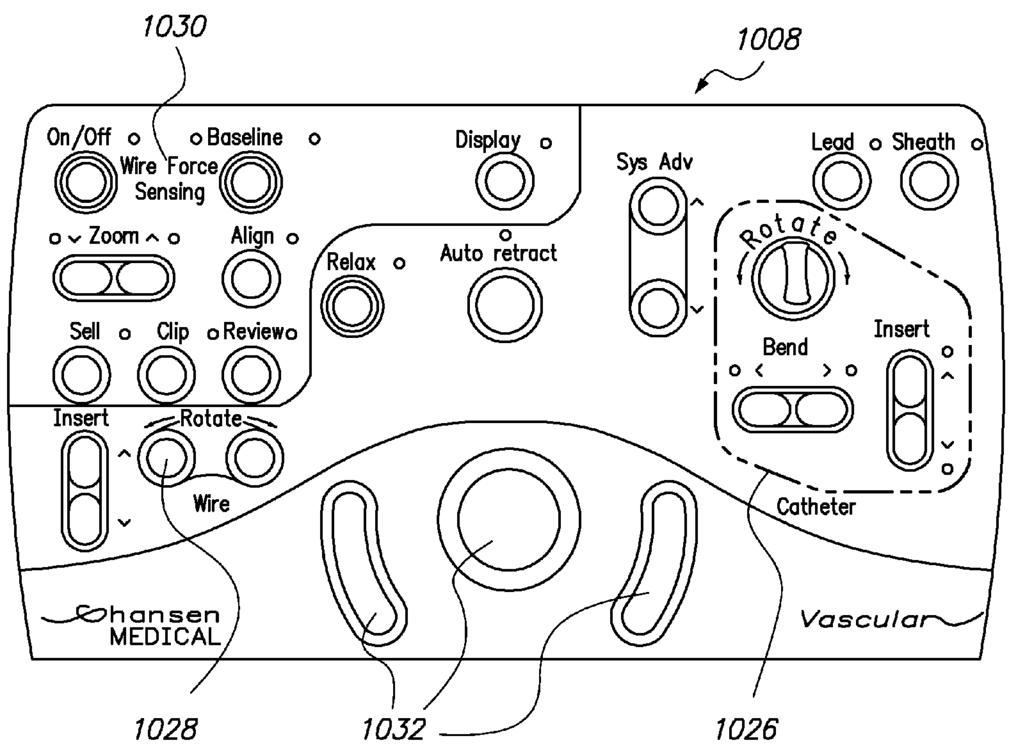

1030
1008
On/Off
Baseline
Wire Force
Sensing
Display
Sys Adv
Lead
Sheath
Zoom
Align
Relax
Auto retract
Rotate
Sell
Clip
Review
Bend
Insert
Insert
Rotate
Wire
Catheter
hansen
MEDICAL
Vascular
1028
1032
1026

FIG. 113

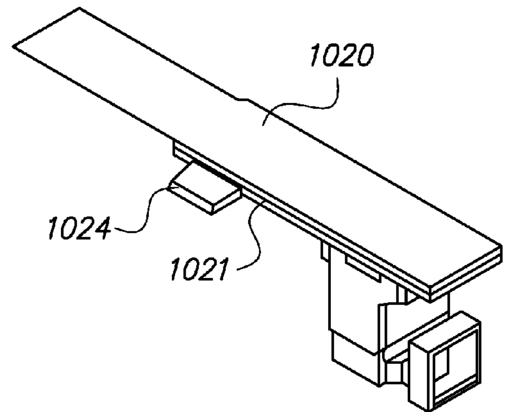


FIG. 114A

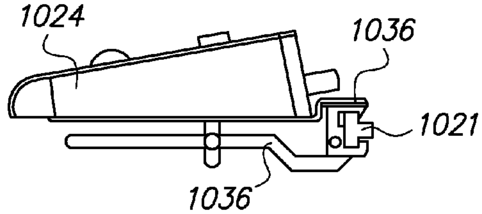


FIG. 114B

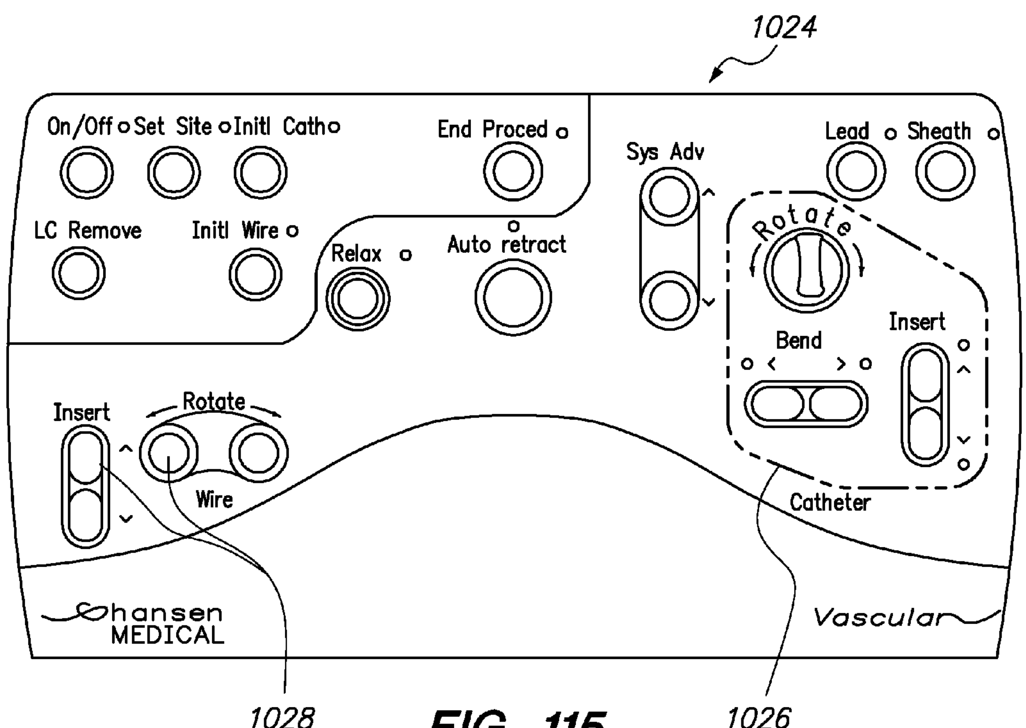


FIG. 115

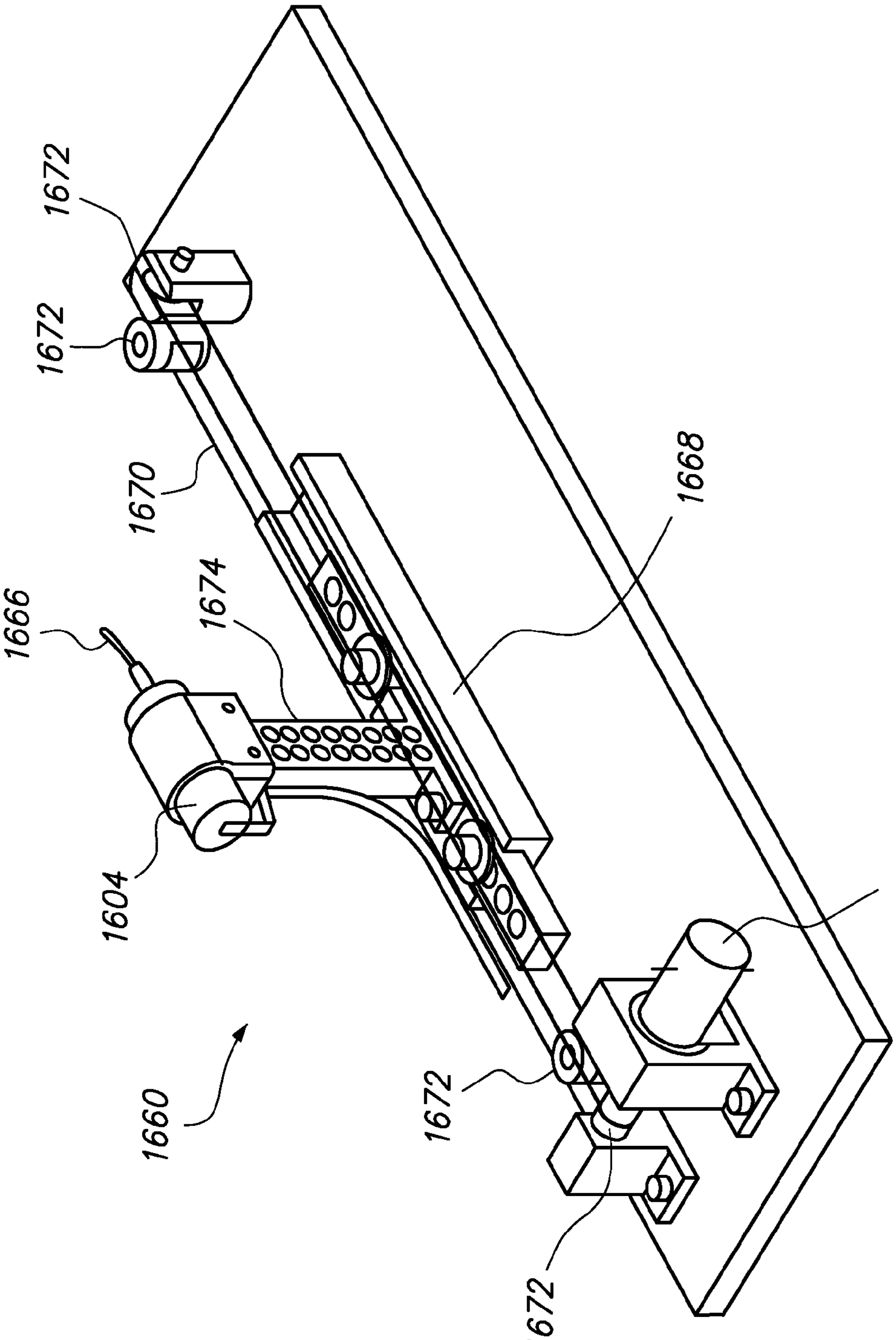


FIG. 116

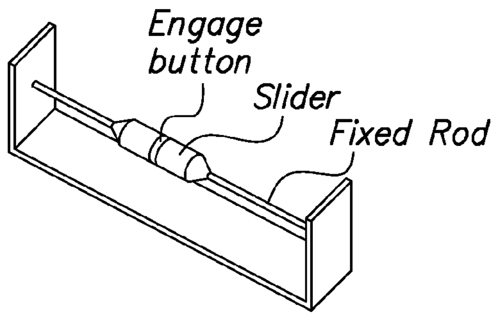


FIG. 117A

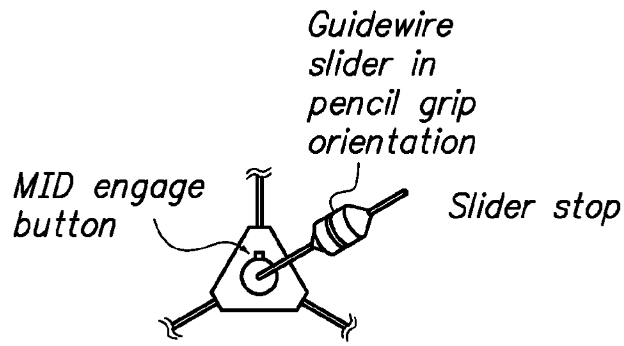


FIG. 117AA

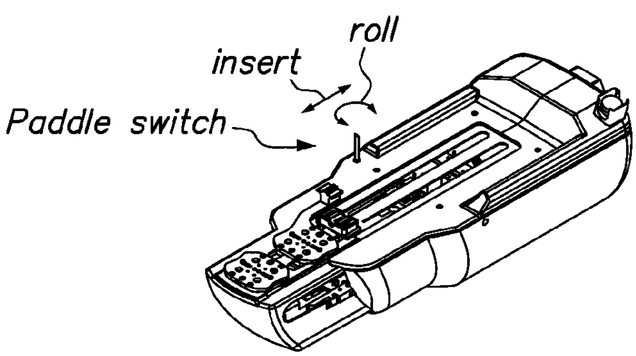


FIG. 117B

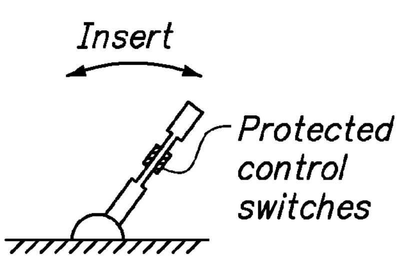


FIG. 117BB

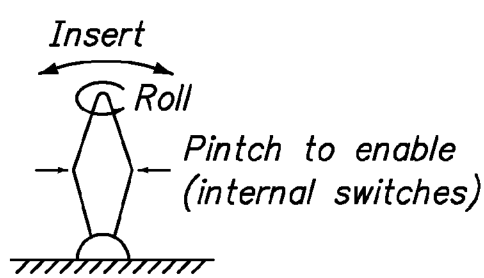


FIG. 117BBB

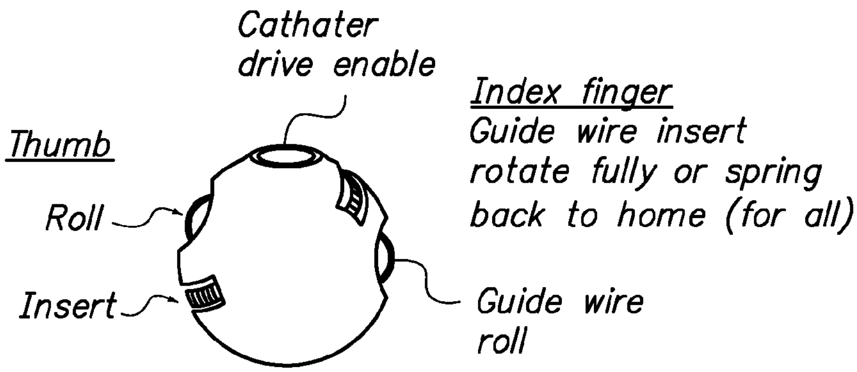


FIG. 117C

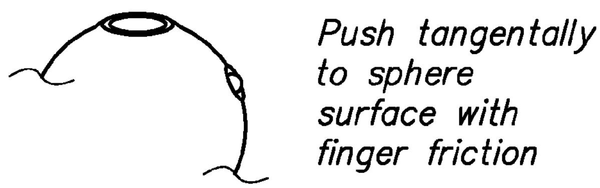


FIG. 117CC

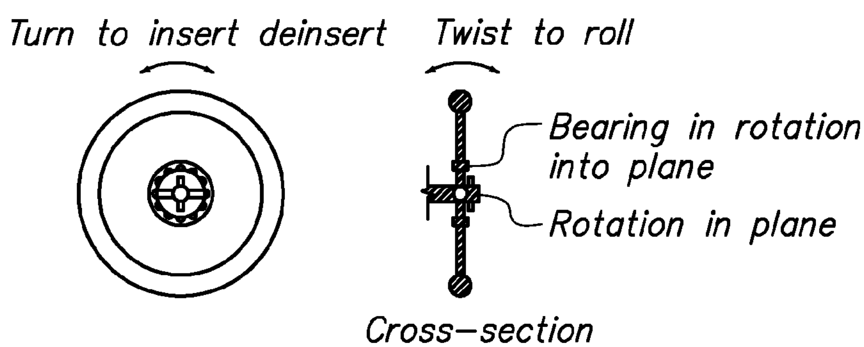


FIG. 117D

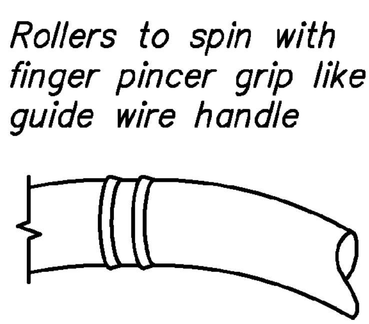


FIG. 117DD

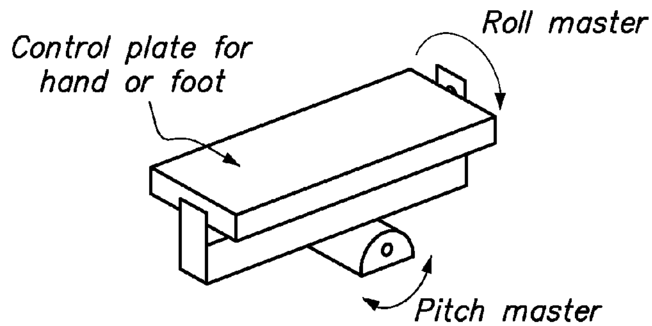


FIG. 117E

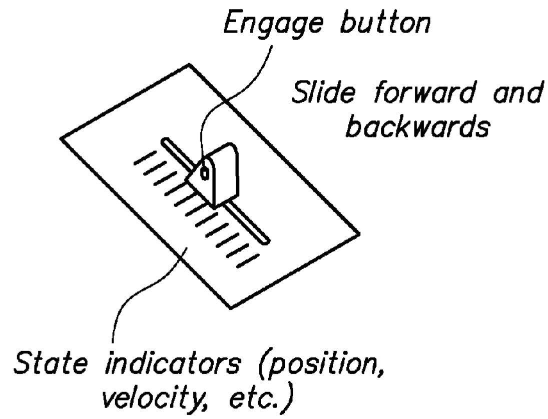


FIG. 117F

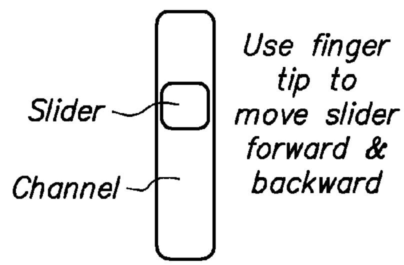


FIG. 117FF

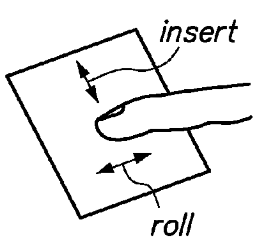


FIG. 117G

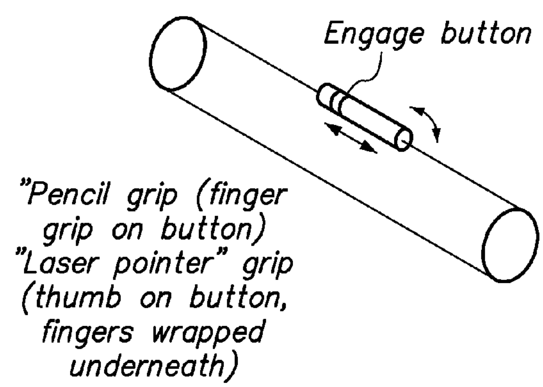


FIG. 117H

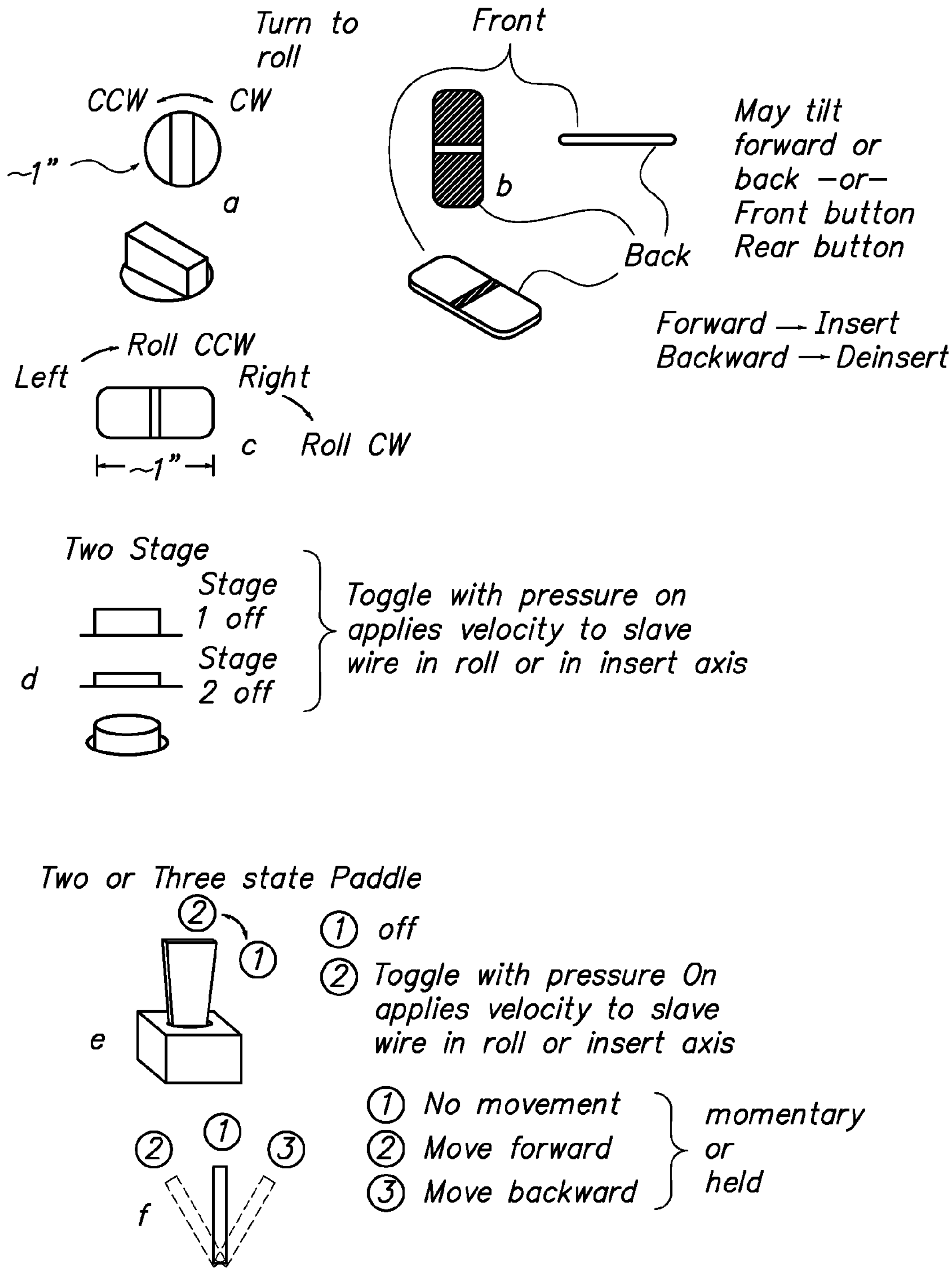

Turn to roll
CCW
CW
~1"
a
Front
b
May tilt forward or back –or– Front button Rear button
Back
Forward → Insert
Backward → Deinsert
Roll CCW
Left
Right
Roll CW
c
~1"
Two Stage
Stage 1 off
Stage 2 off
d
Toggle with pressure on applies velocity to slave wire in roll or in insert axis
Two or Three state Paddle
2
1
1 off
2 Toggle with pressure On applies velocity to slave wire in roll or insert axis
e
1 No movement
2 Move forward
3 Move backward
momentary or held
2
1
3
f

FIG. 117I

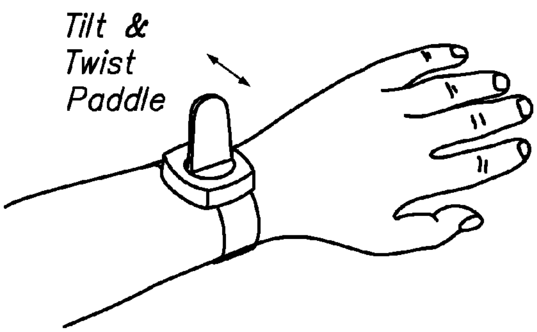


FIG. 117J

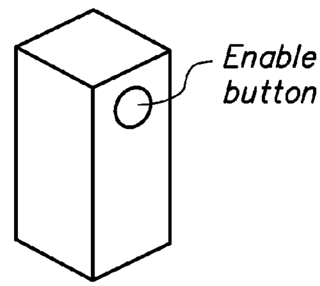


FIG. 117K

Finger Trap

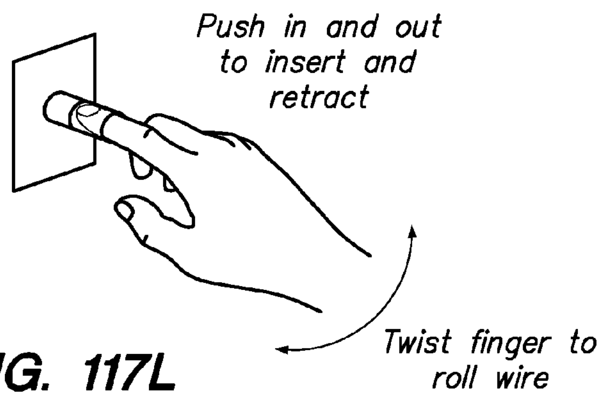


FIG. 117L

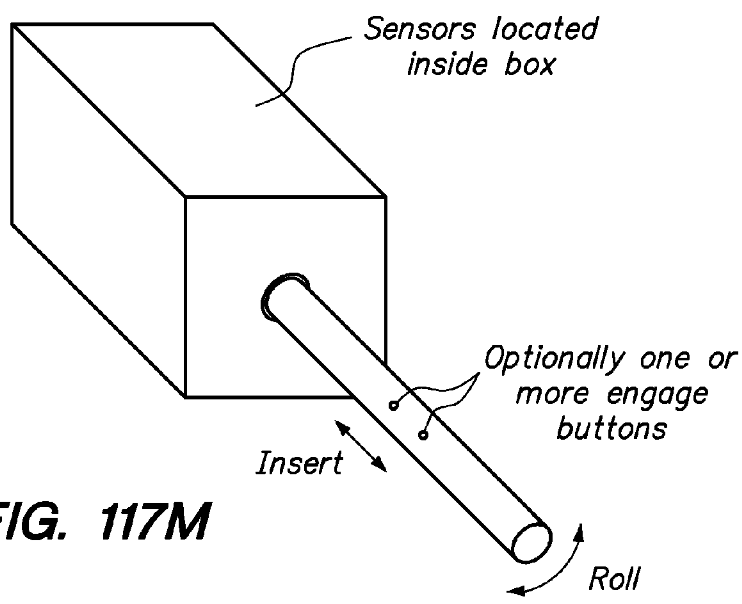


FIG. 117M

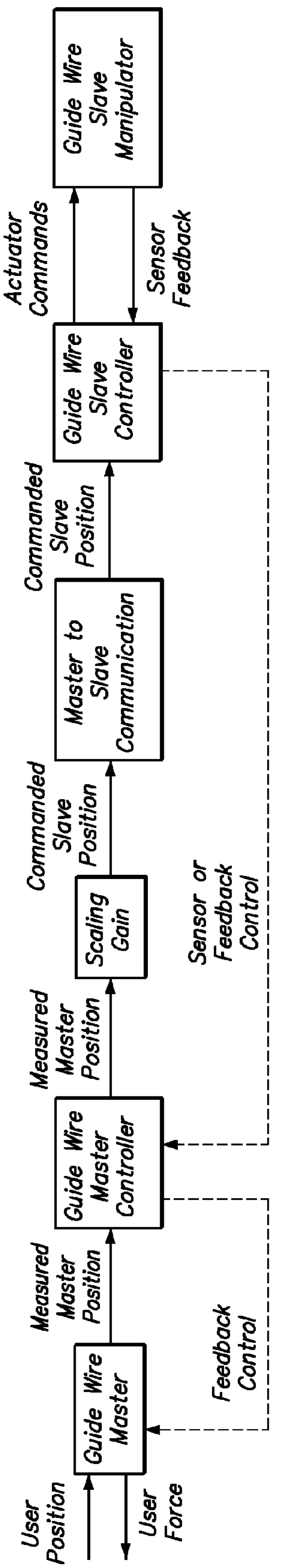


FIG. 118A

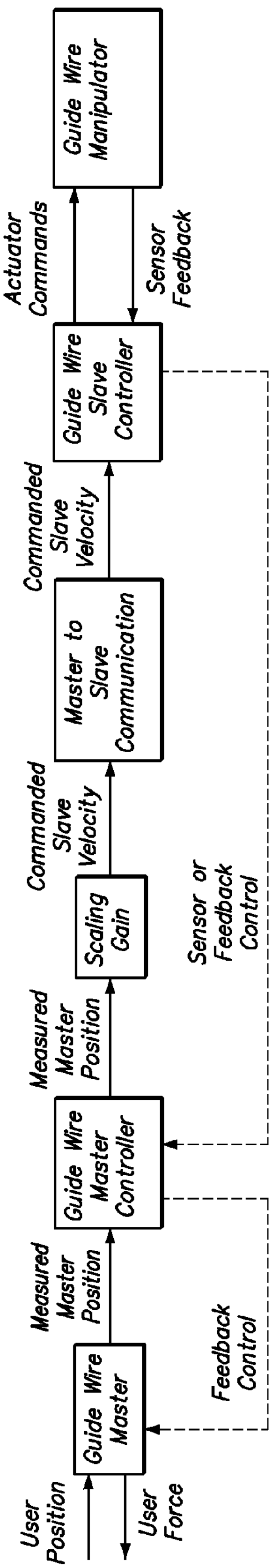


FIG. 118B

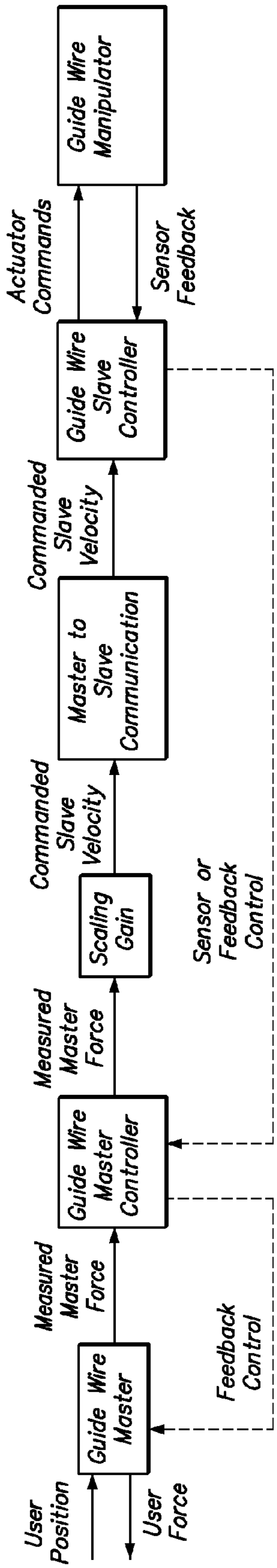


FIG. 118C

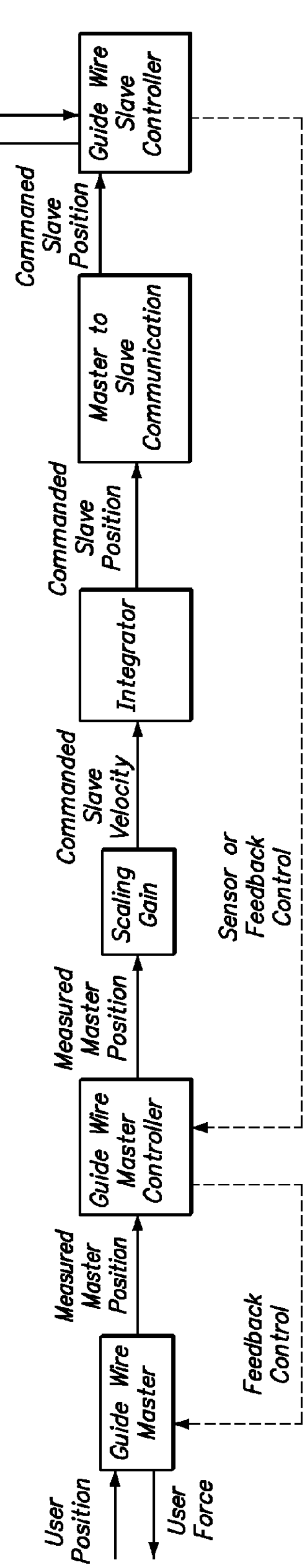


FIG. 118D

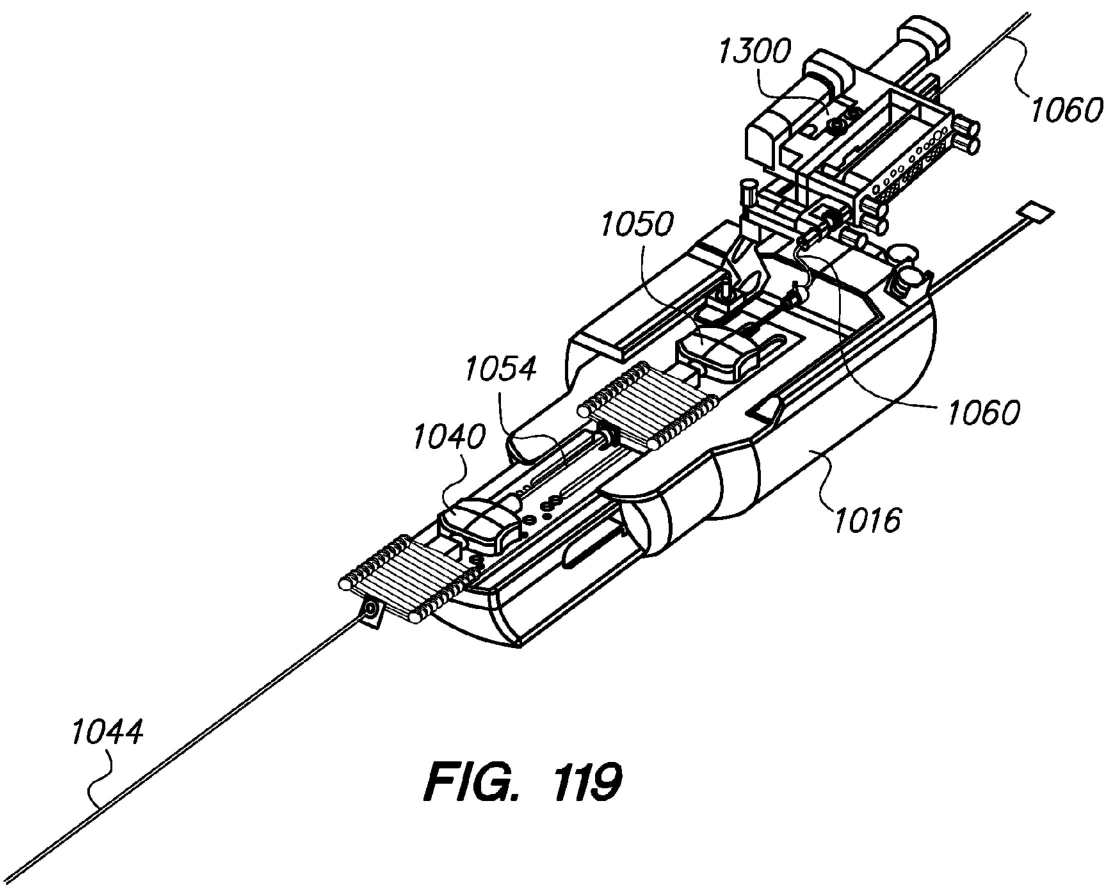


FIG. 119

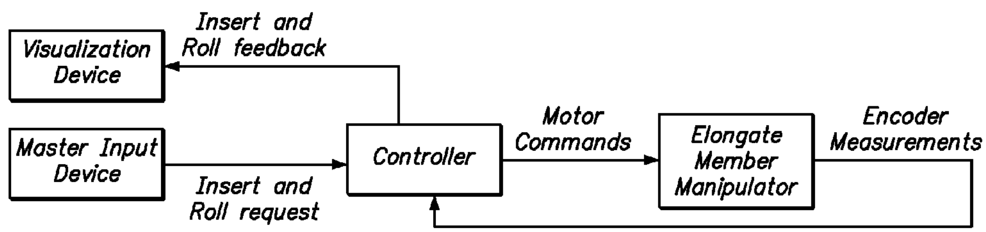


FIG. 120

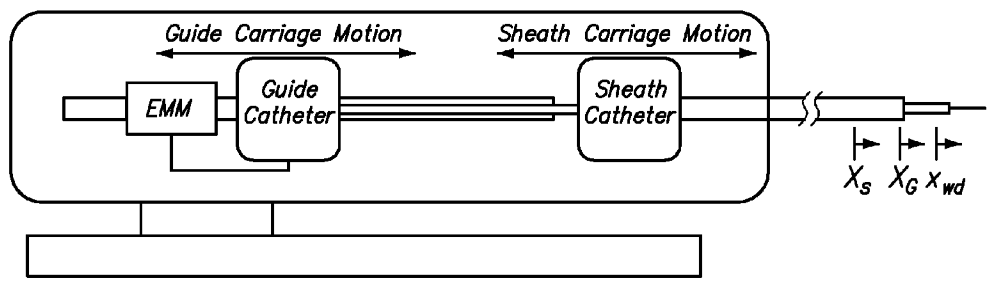


FIG. 121A

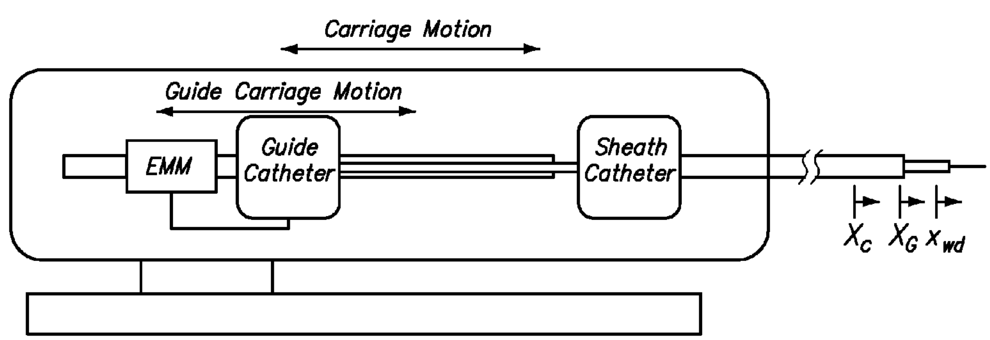


FIG. 121B

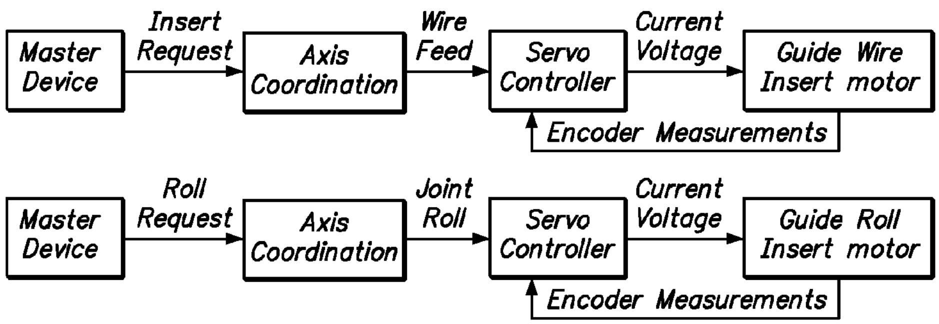


FIG. 122

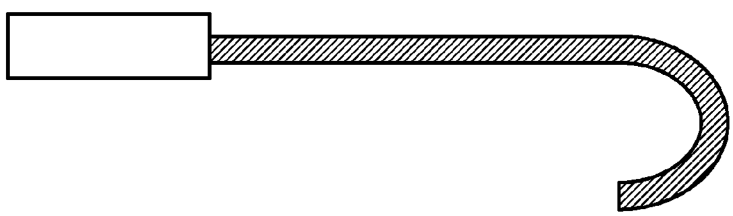


FIG. 123

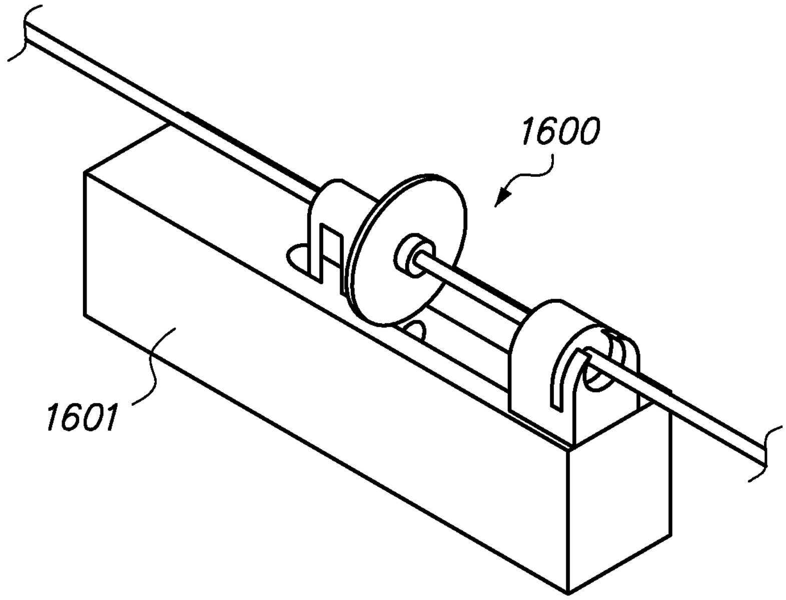


FIG. 124A

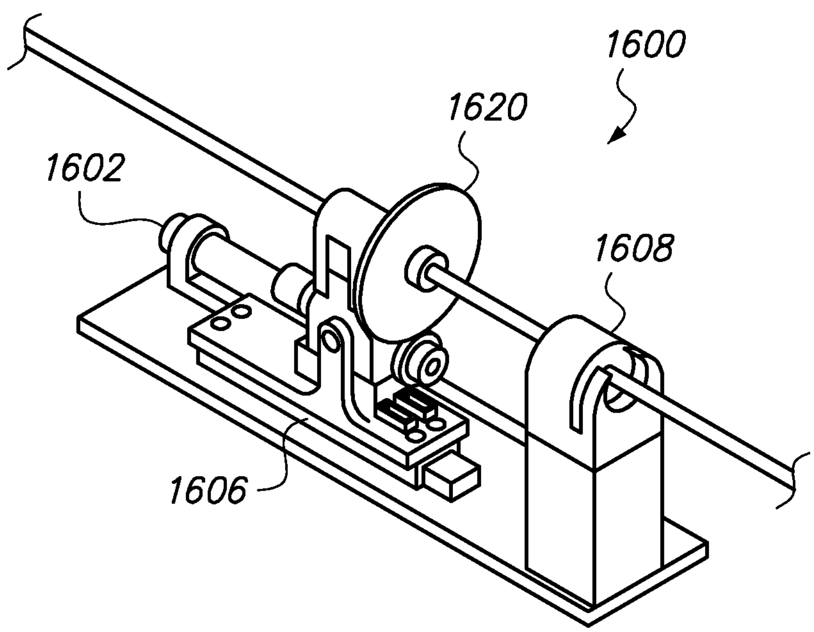


FIG. 124B

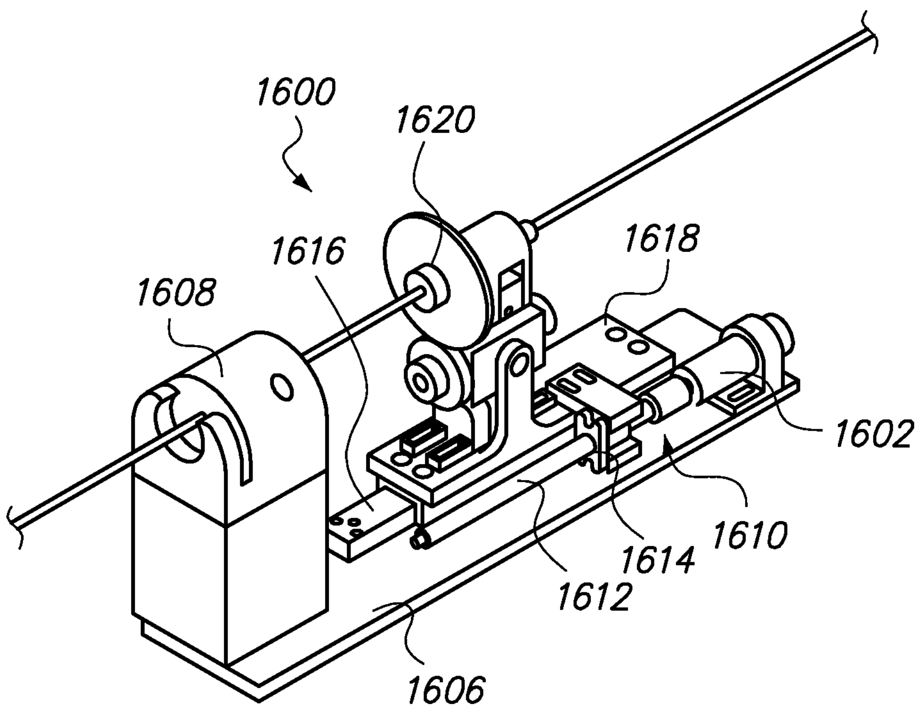


FIG. 124C

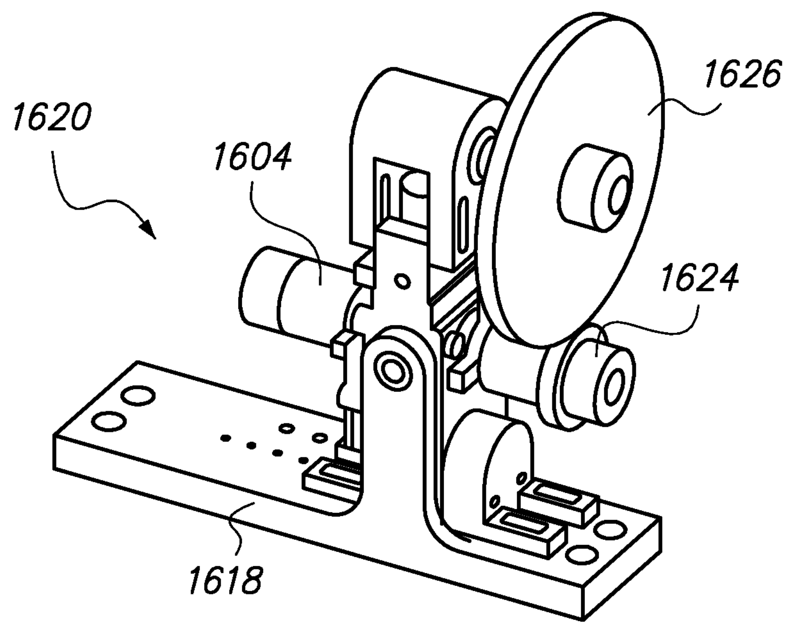


FIG. 125A

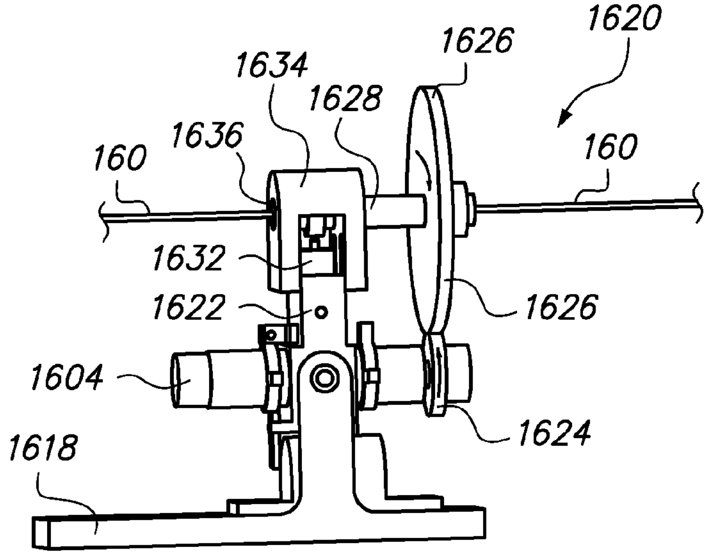


FIG. 125B

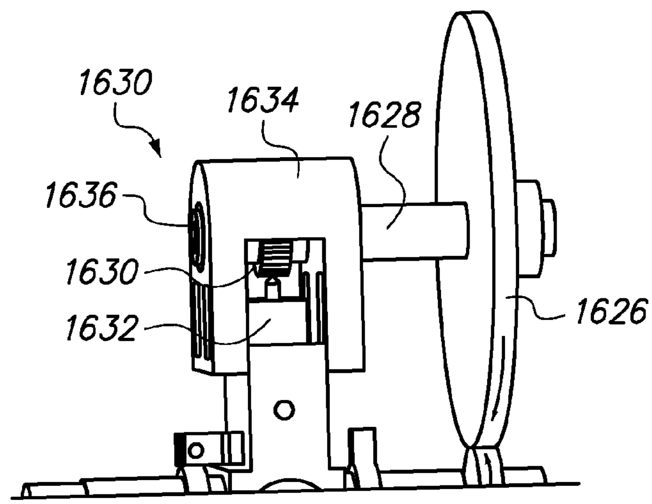


FIG. 125C

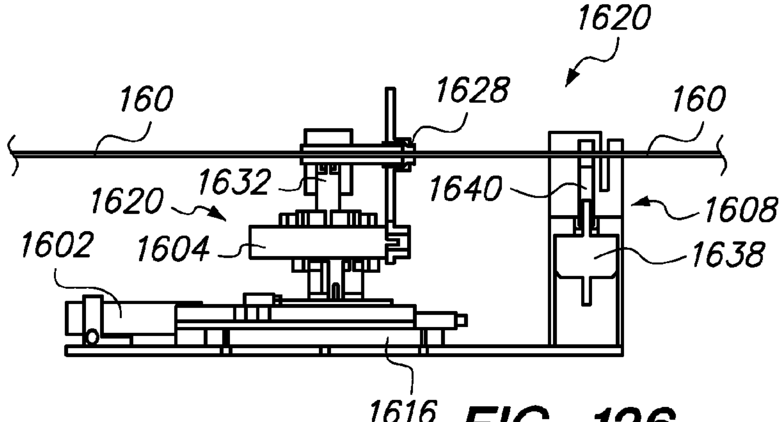


FIG. 126

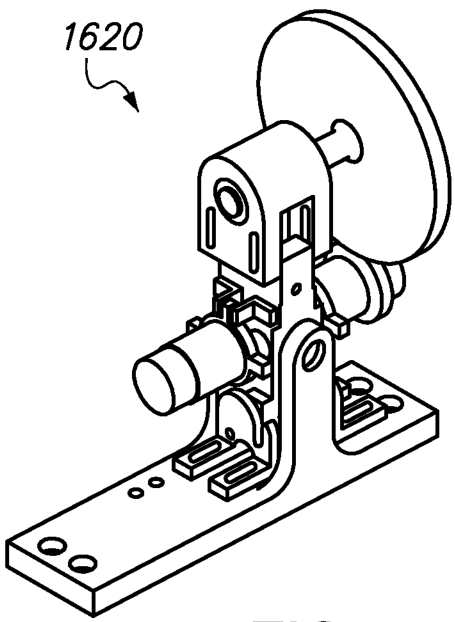


FIG. 127A

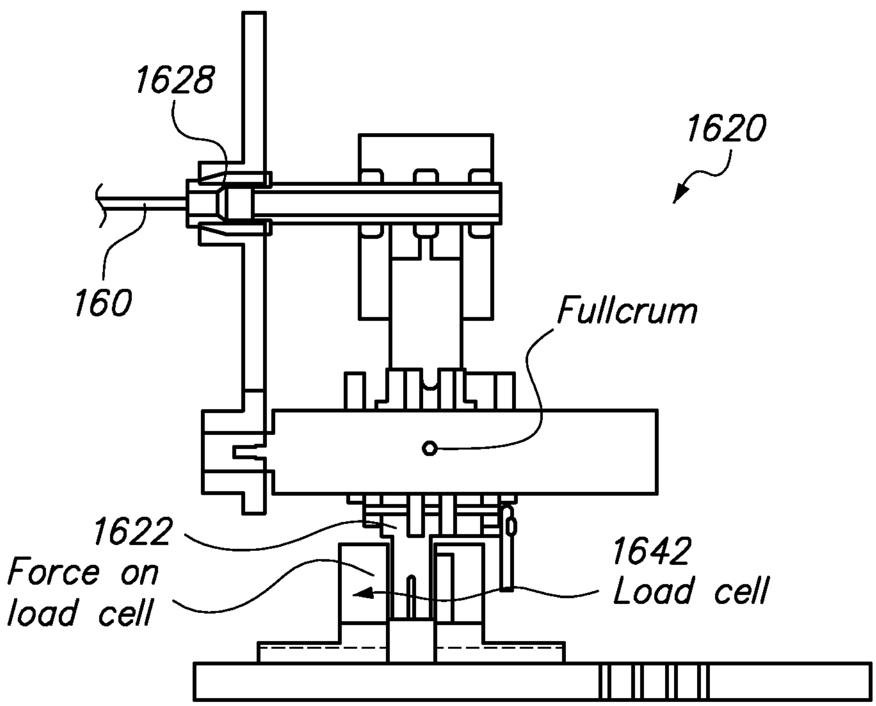


FIG. 127B

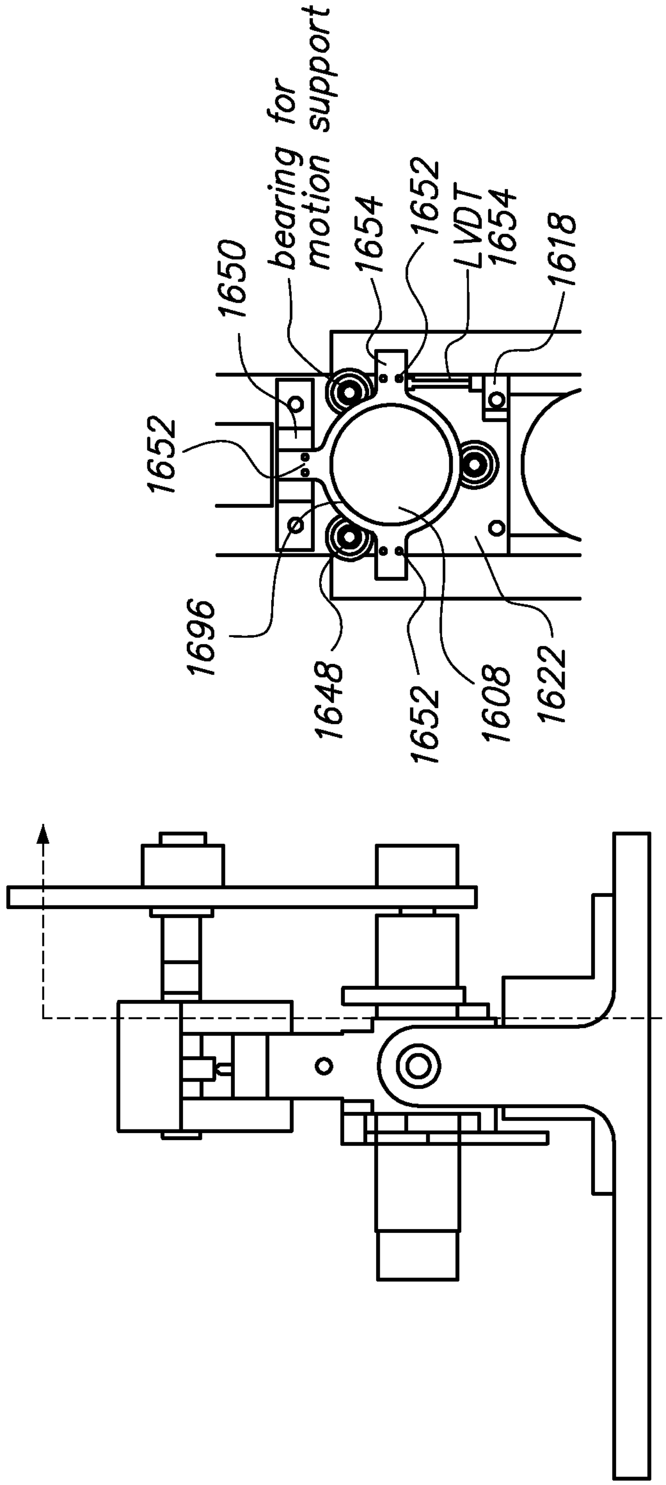

bearing for motion support
1650
1654
1652
LVDT
1654
1618
1652
1696
1648
1652
1608
1622

FIG. 127C

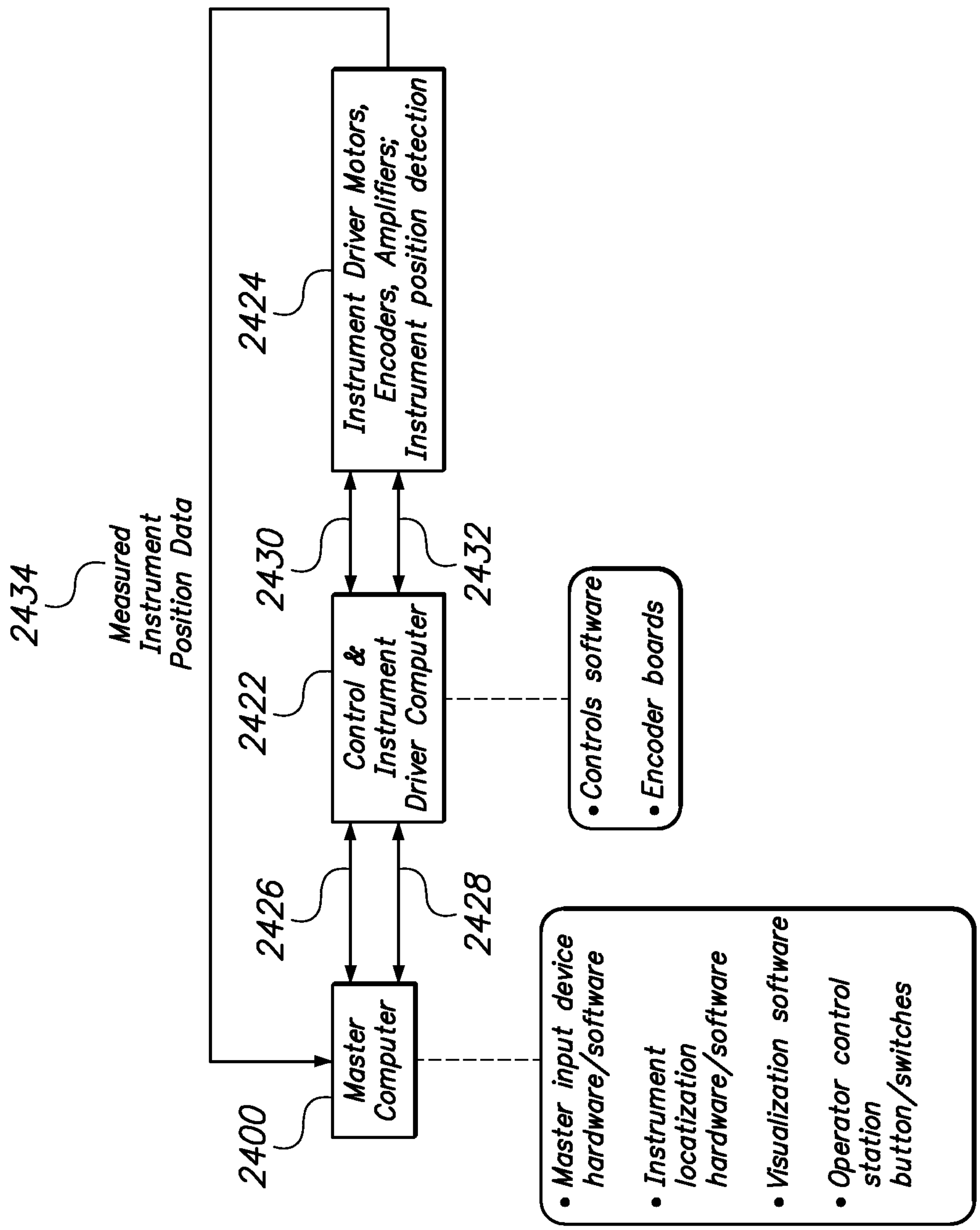

2434
Measured Instrument Position Data
2424
Instrument Driver Motors, Encoders, Amplifiers; Instrument position detection
2430
2432
2422
Control & Instrument Driver Computer
• Controls software
• Encoder boards
2426
2428
2400
Master Computer
• Master input device hardware/software
• Instrument locatization hardware/software
• Visualization software
• Operator control station button/switches

FIG. 128A

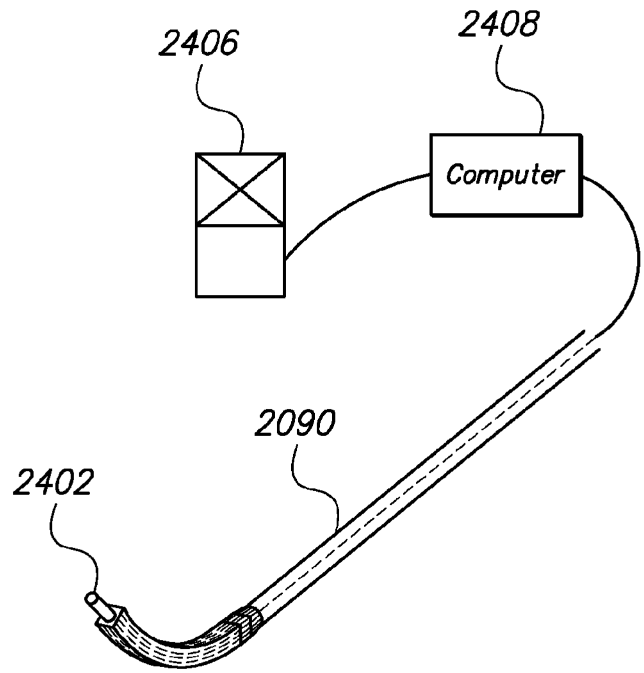


FIG. 128B

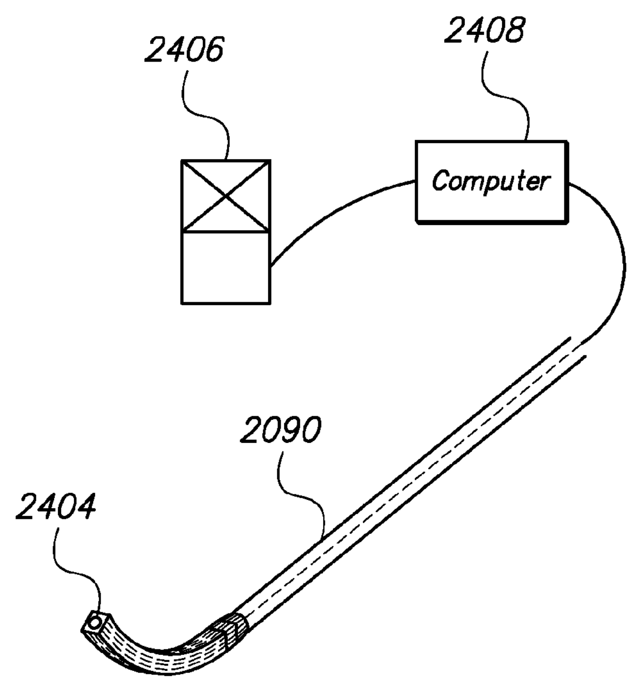


FIG. 128C

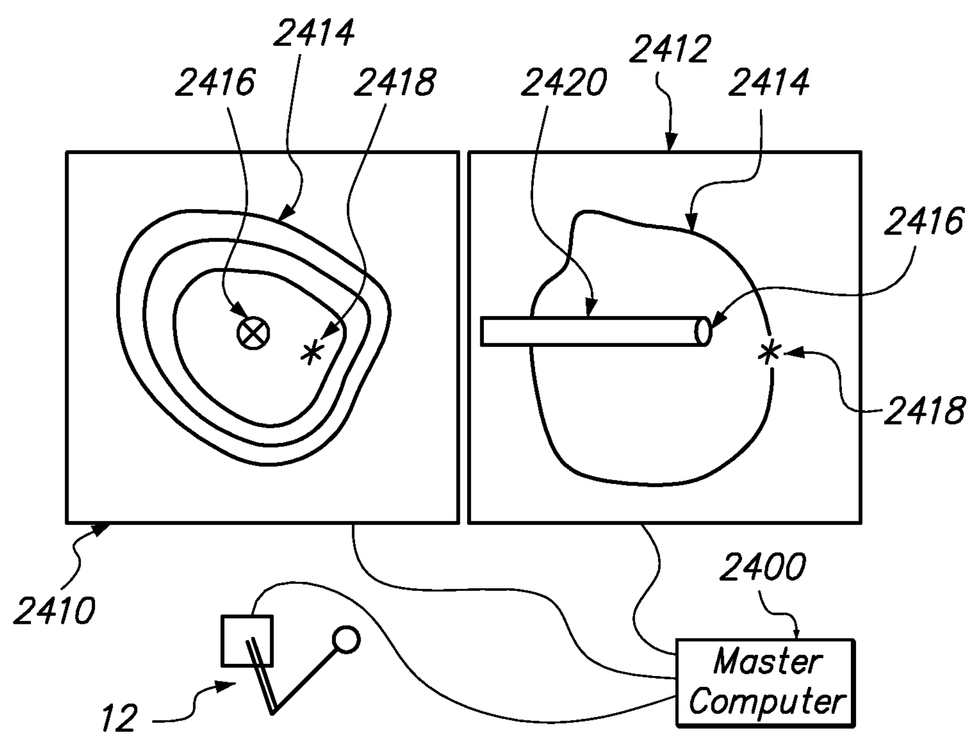

2414
2416
2418
2420
2412
2414
2416
2418
2410
2400
Master Computer
12

FIG. 128D

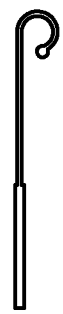


FIG. 128E

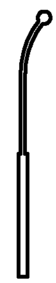


FIG. 128F

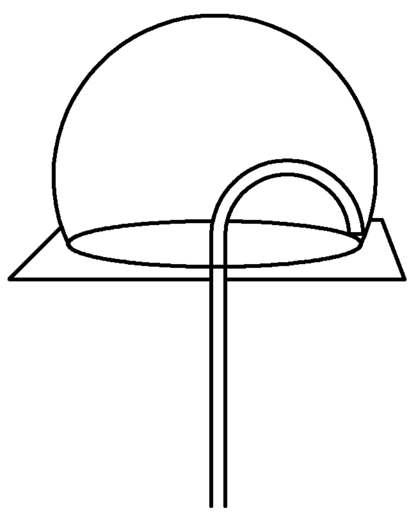


FIG. 128G

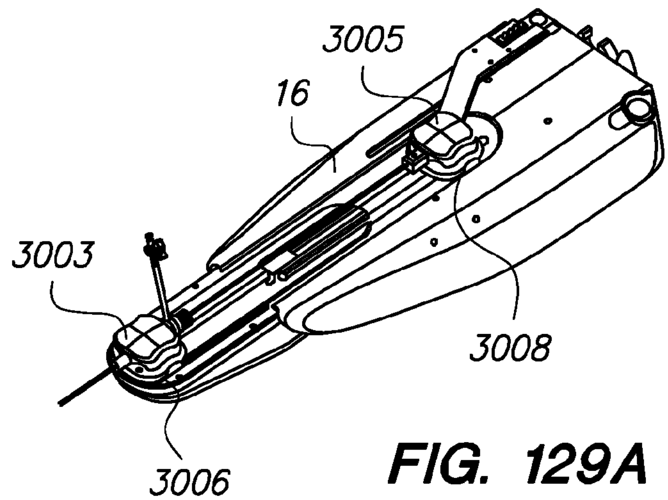


FIG. 129A

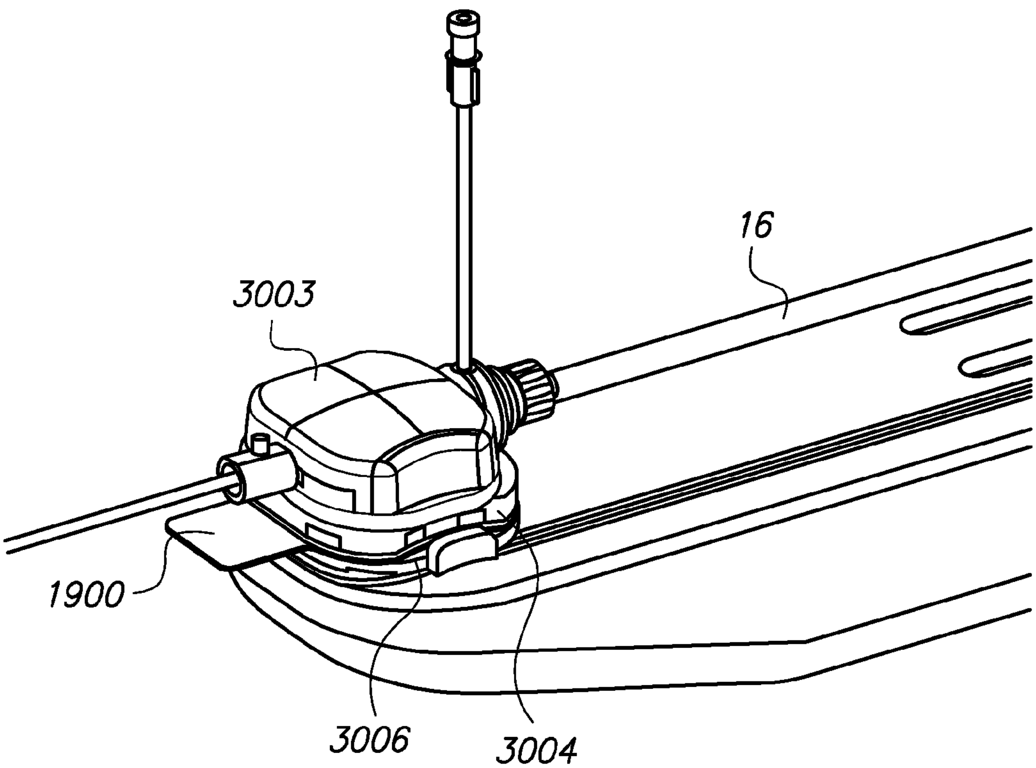


FIG. 129B

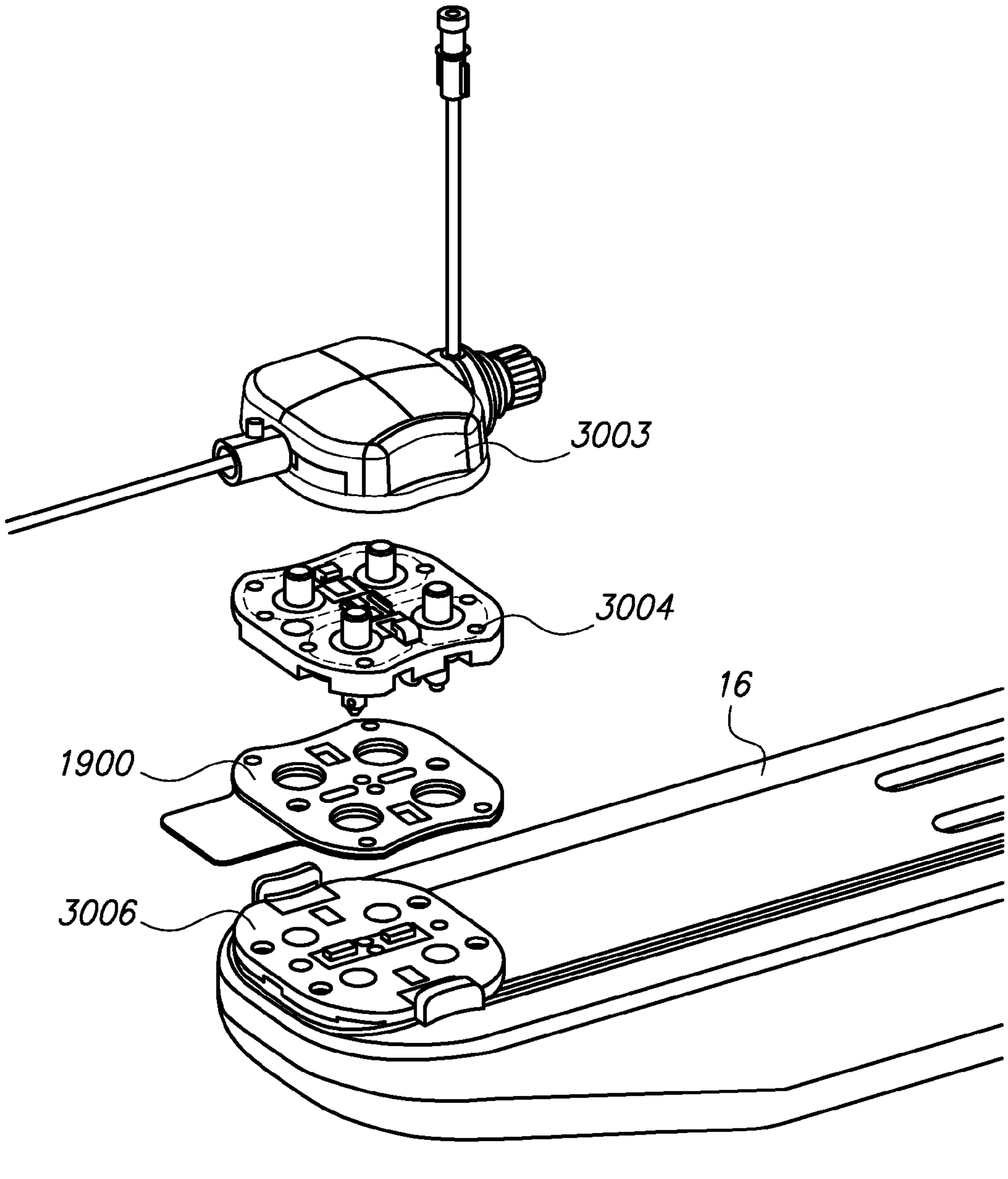


FIG. 129C

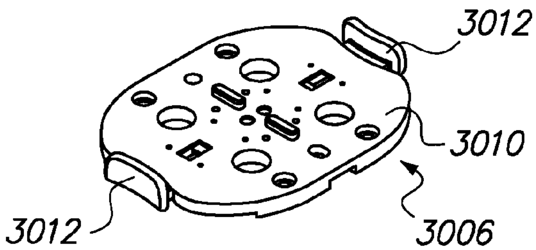


FIG. 130A

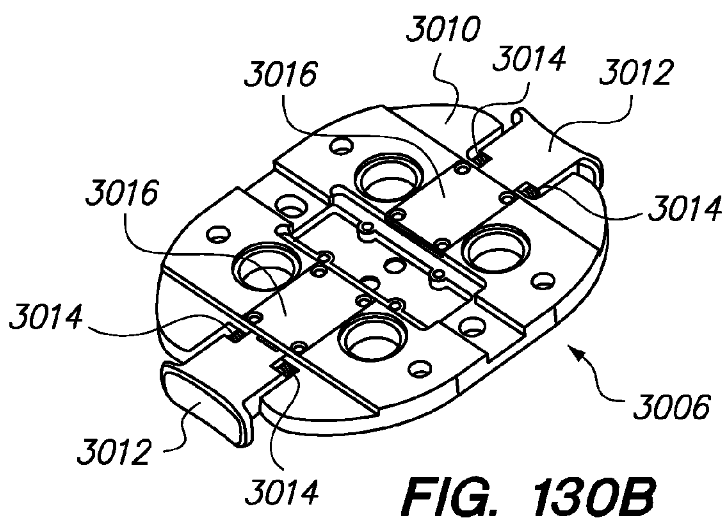


FIG. 130B

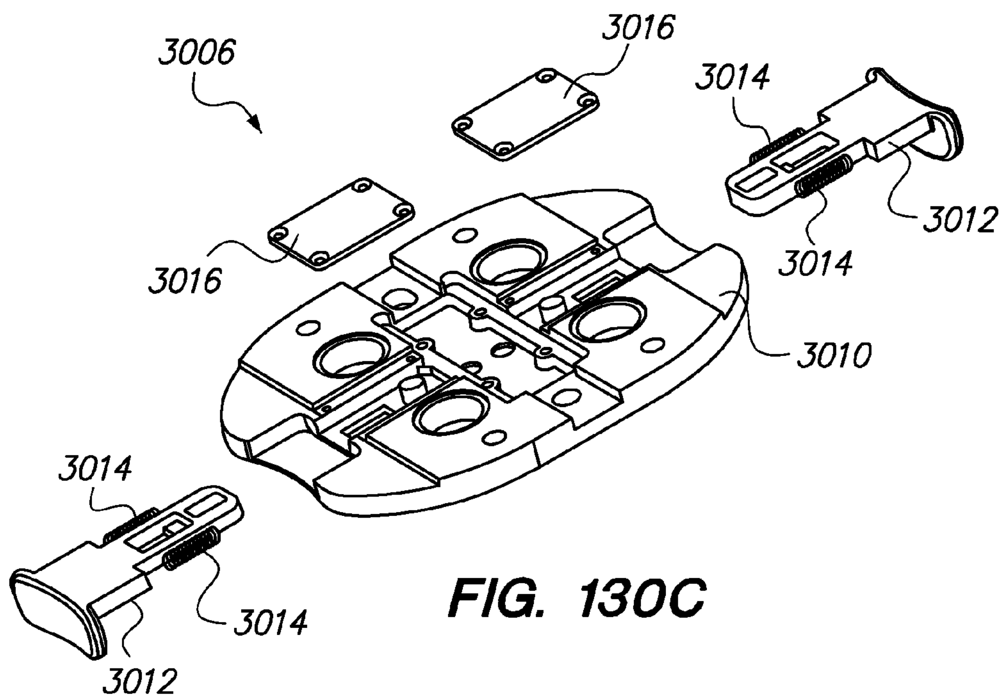


FIG. 130C

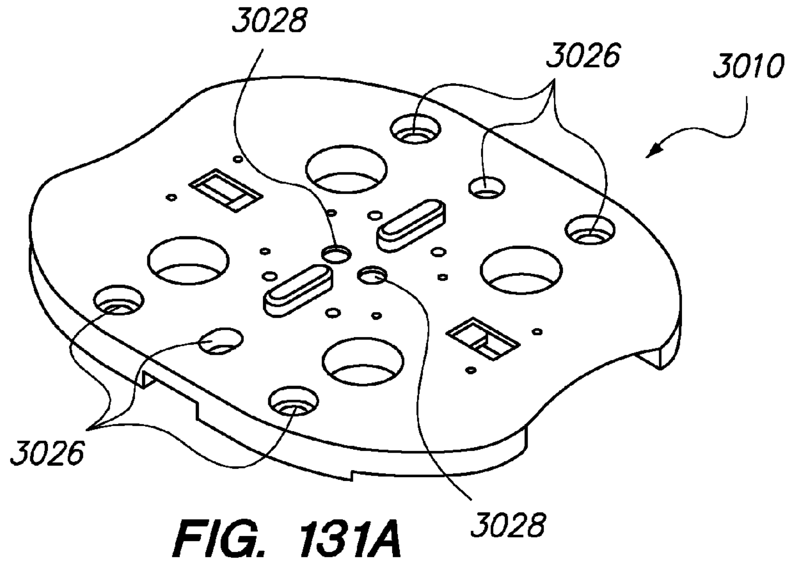


FIG. 131A

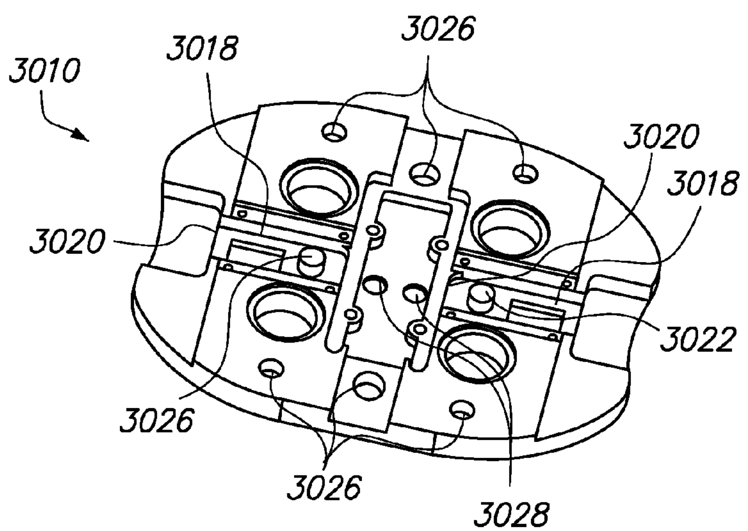


FIG. 131B

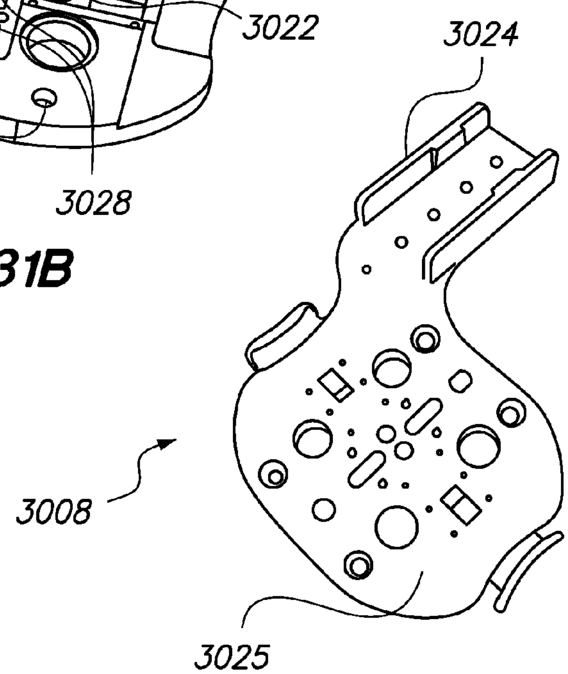


FIG. 131C

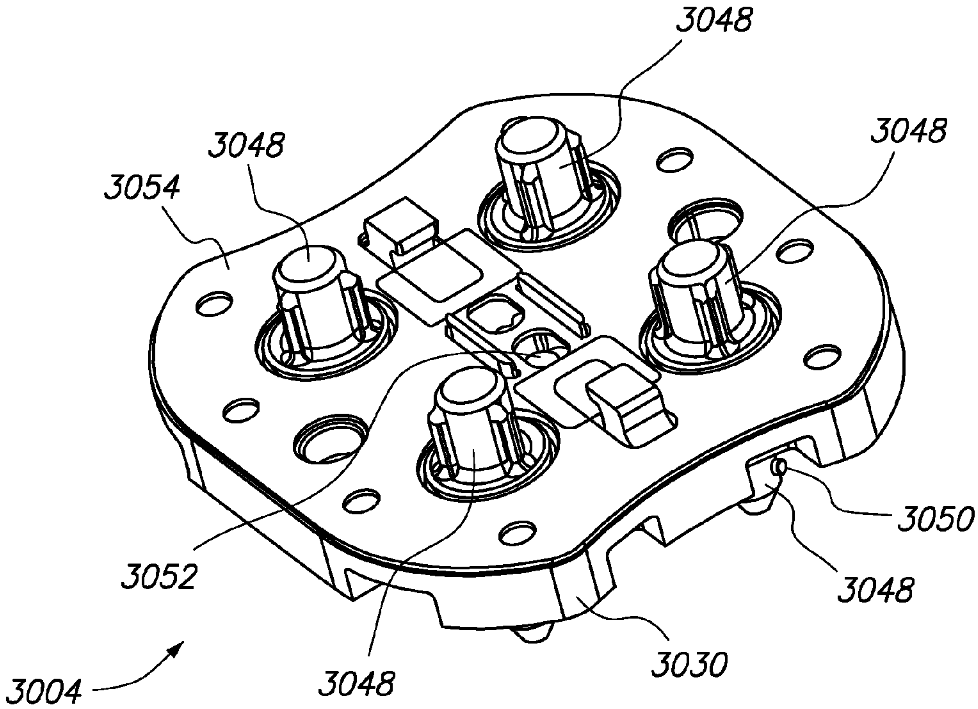


FIG. 132A

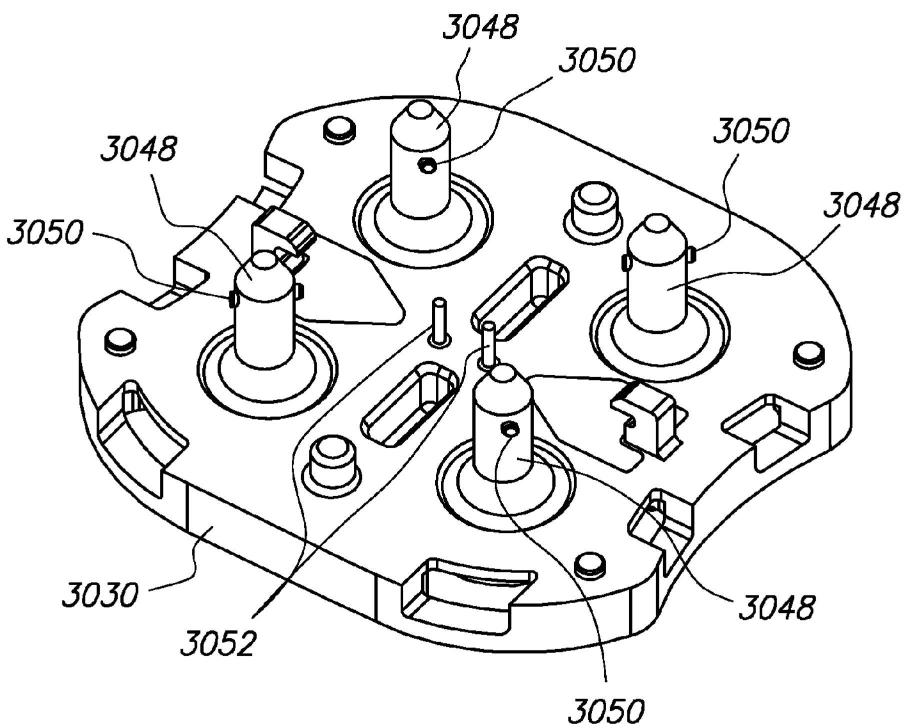


FIG. 132B

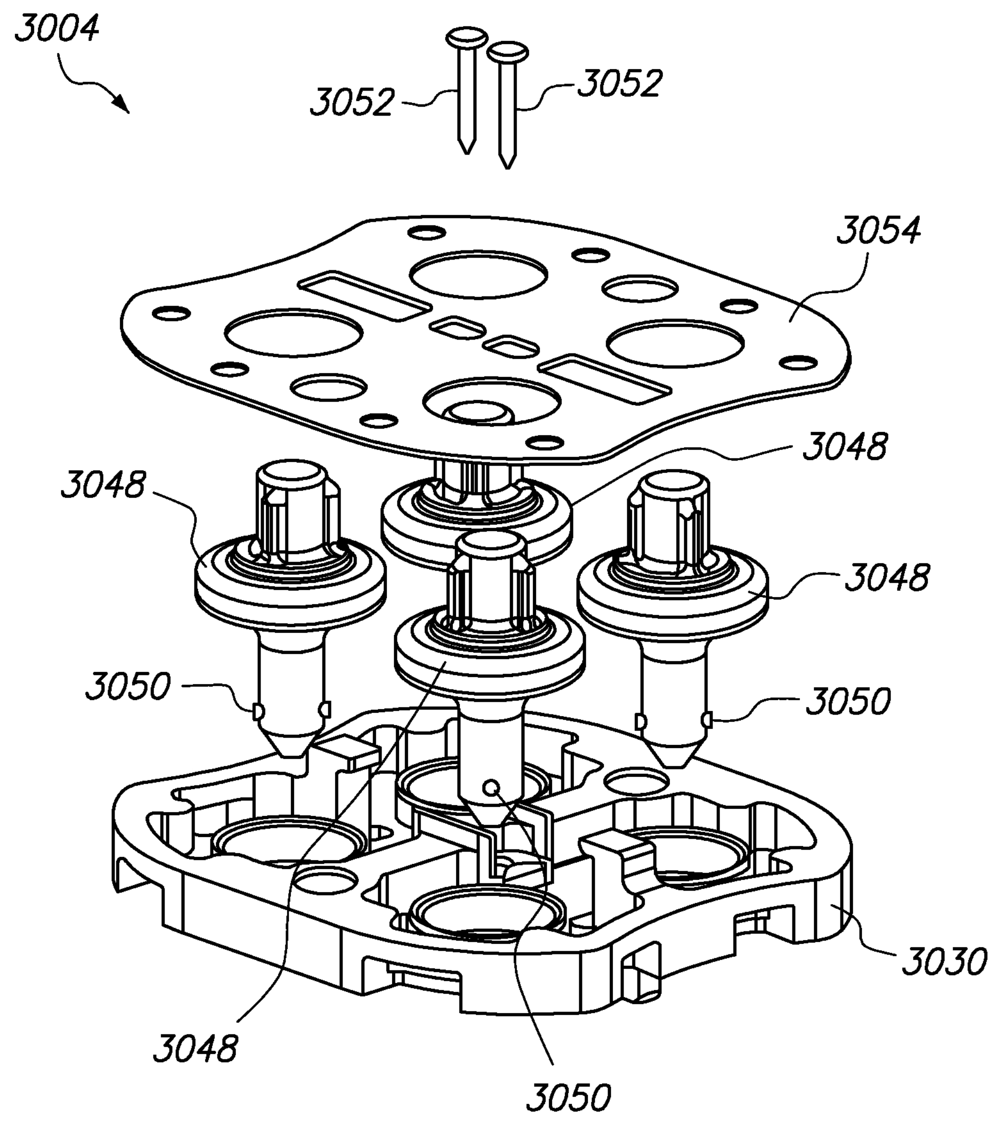


FIG. 132C

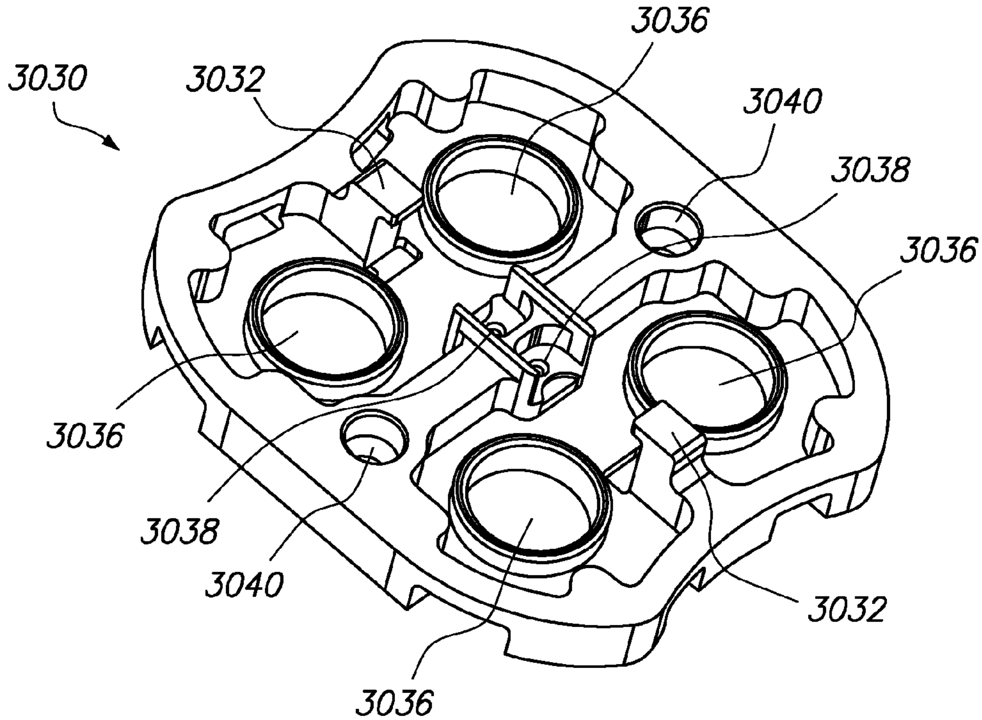


FIG. 133A

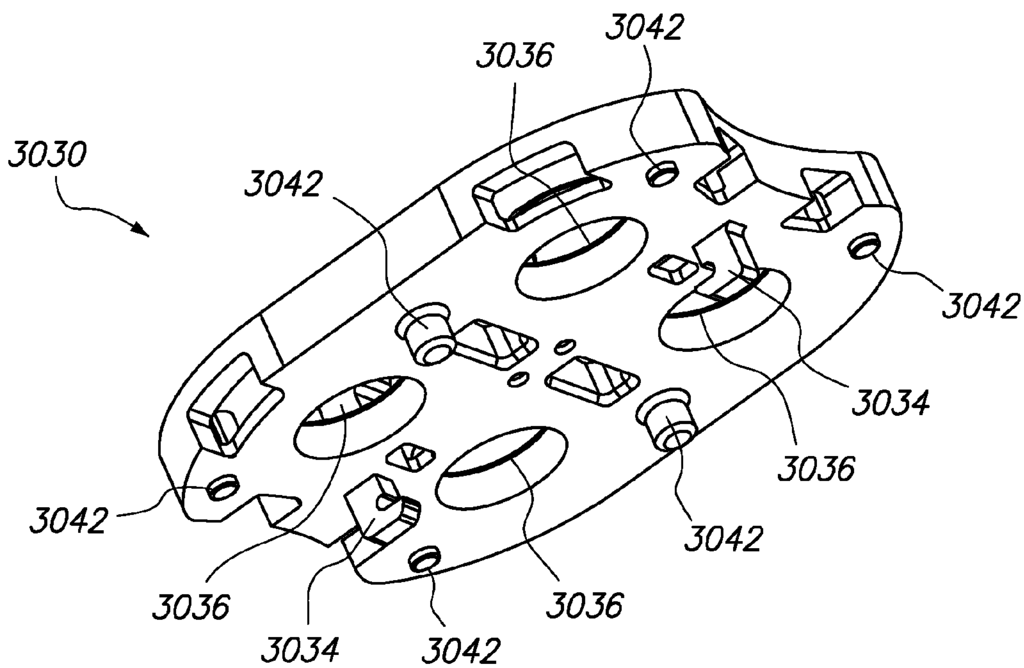


FIG. 133B

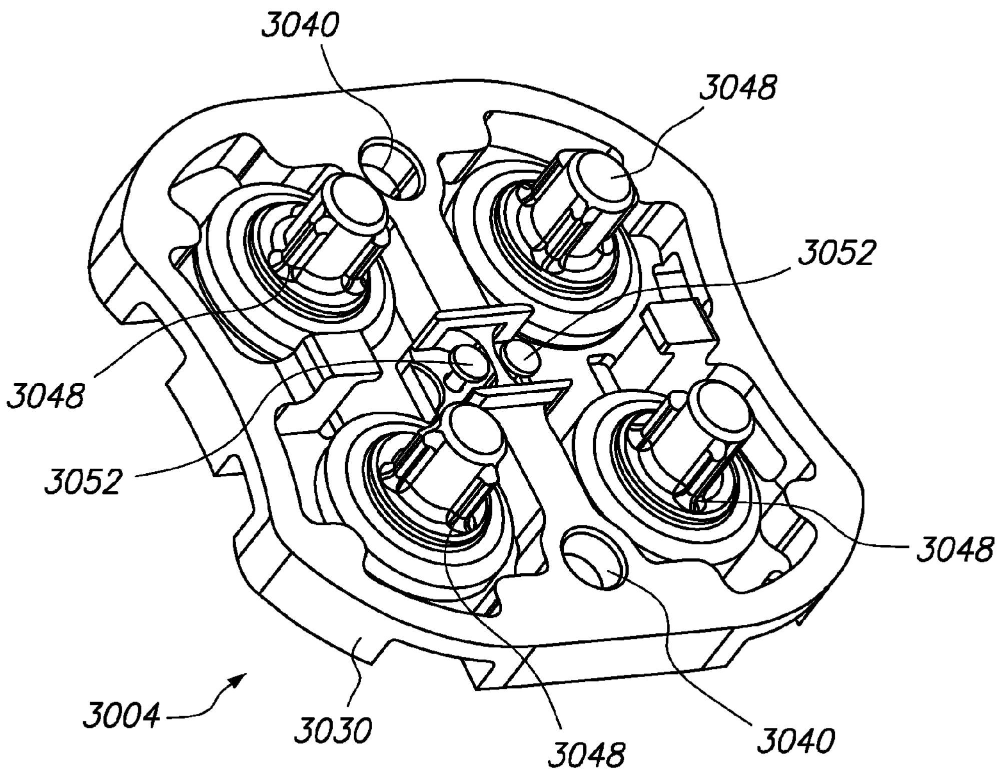


FIG. 134A

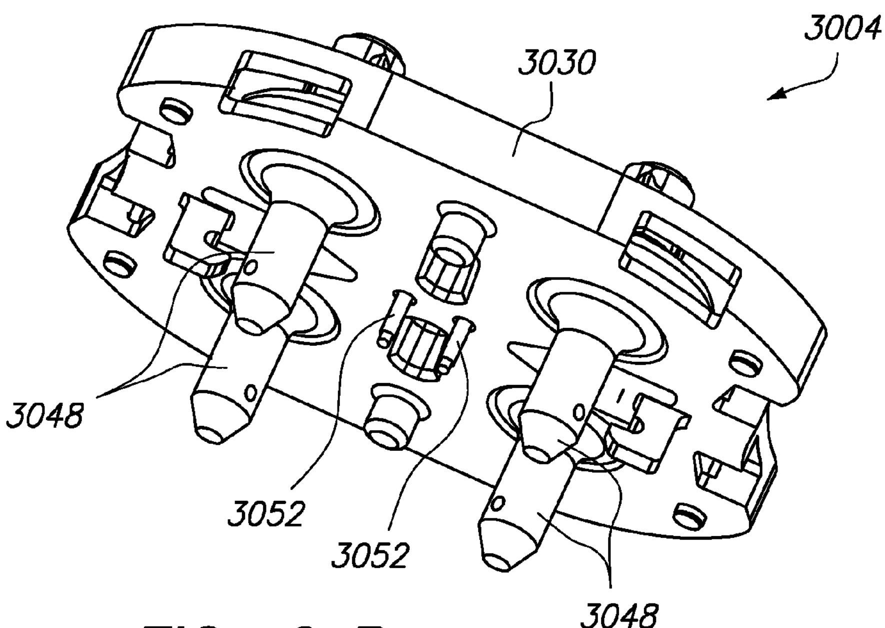


FIG. 134B

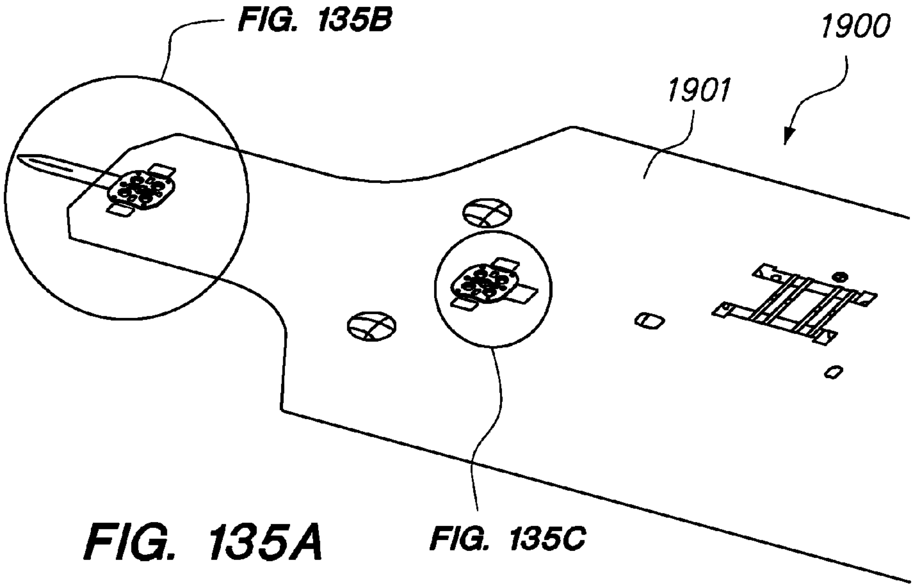


FIG. 135A

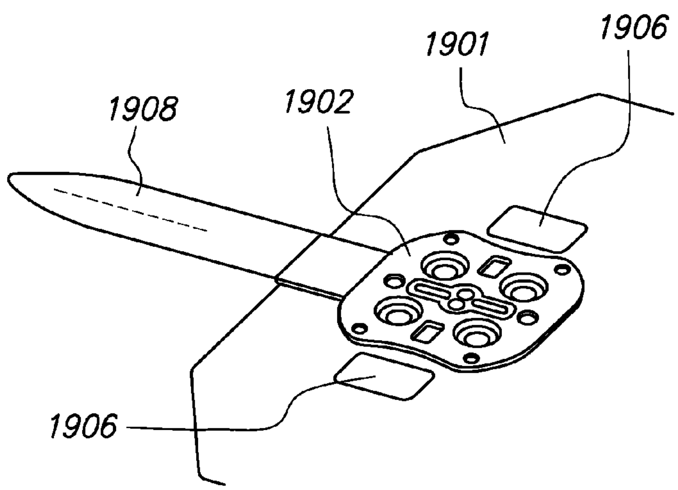


FIG. 135B

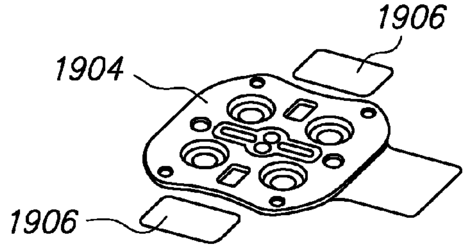


FIG. 135C

FIG. 136A

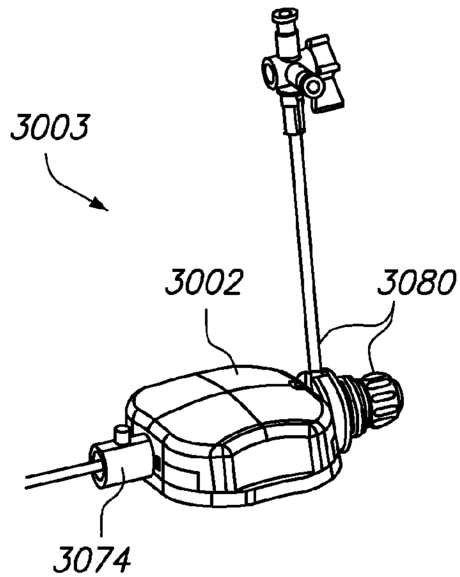


FIG. 136B

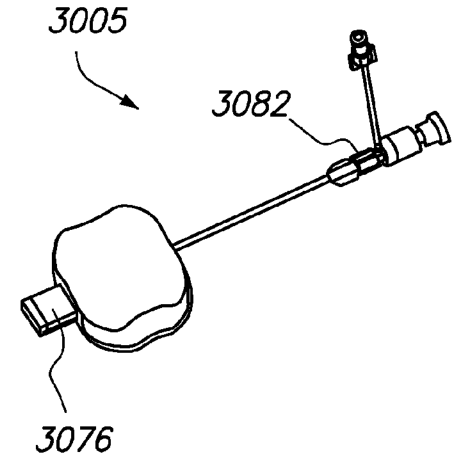
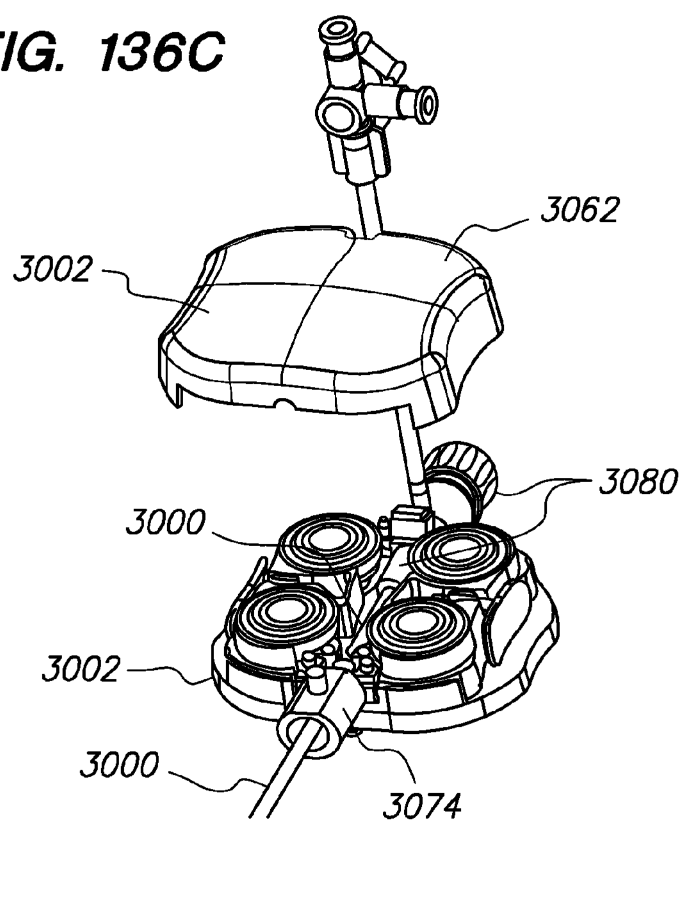


FIG. 136C



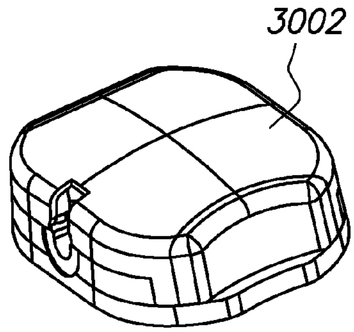


FIG. 137A

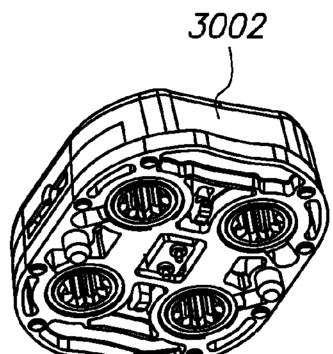


FIG. 137B

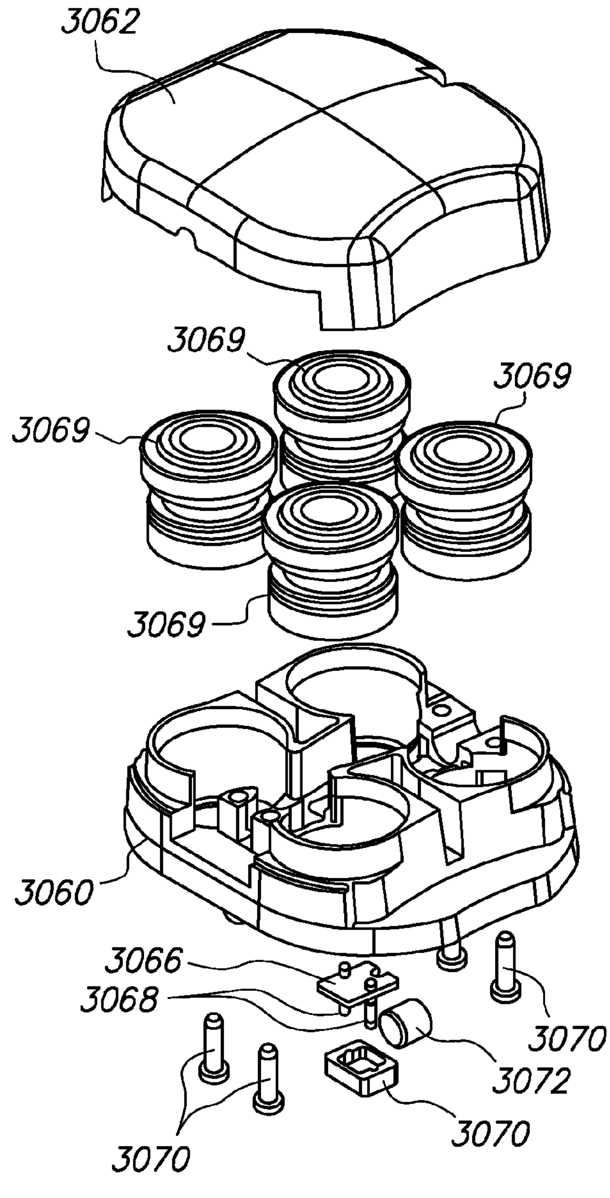
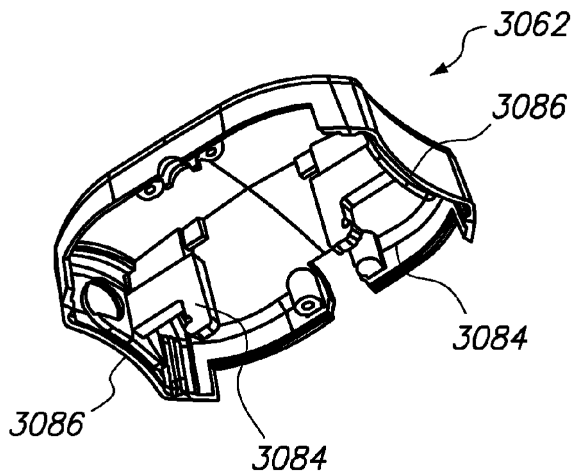


FIG. 137C

FIG. 138



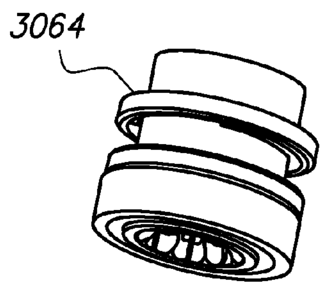


FIG. 138A

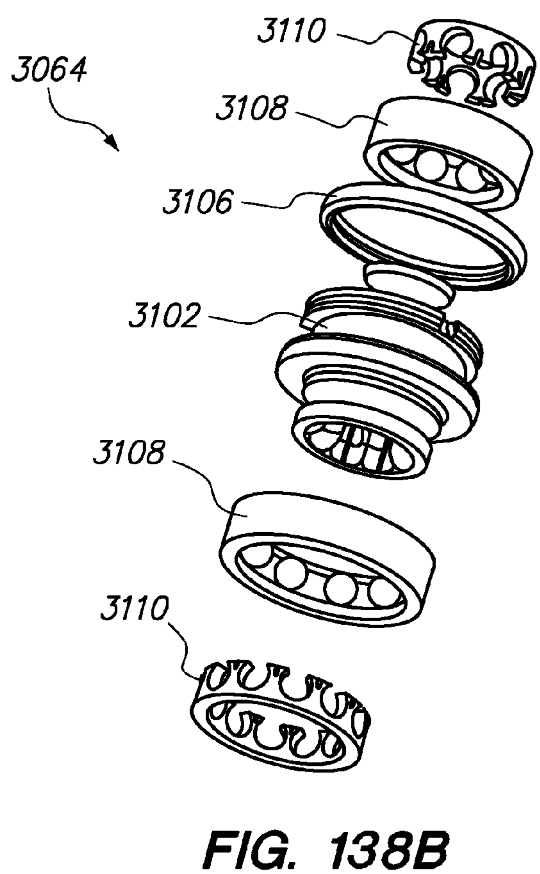


FIG. 138B

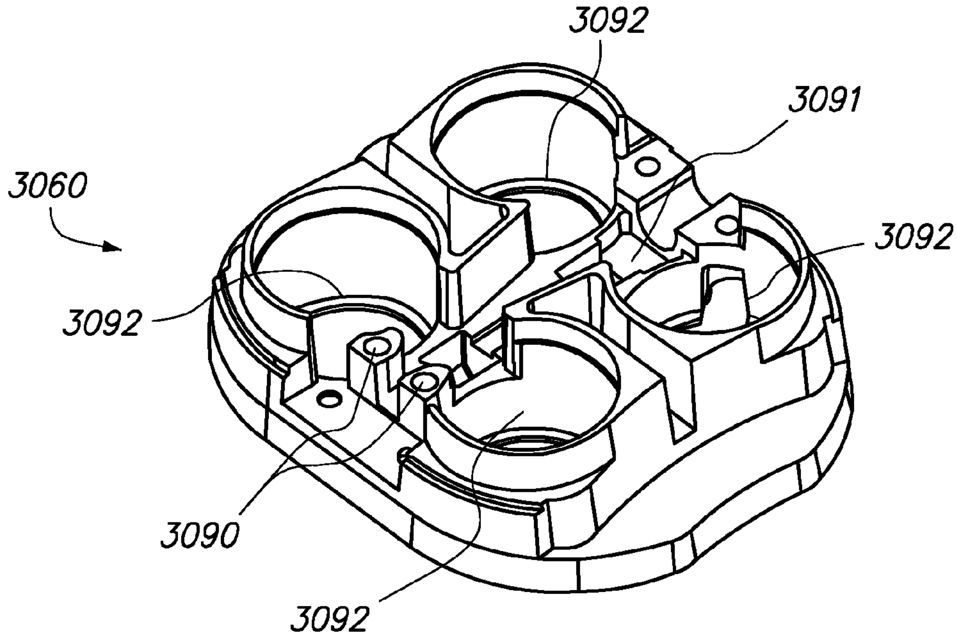


FIG. 139A

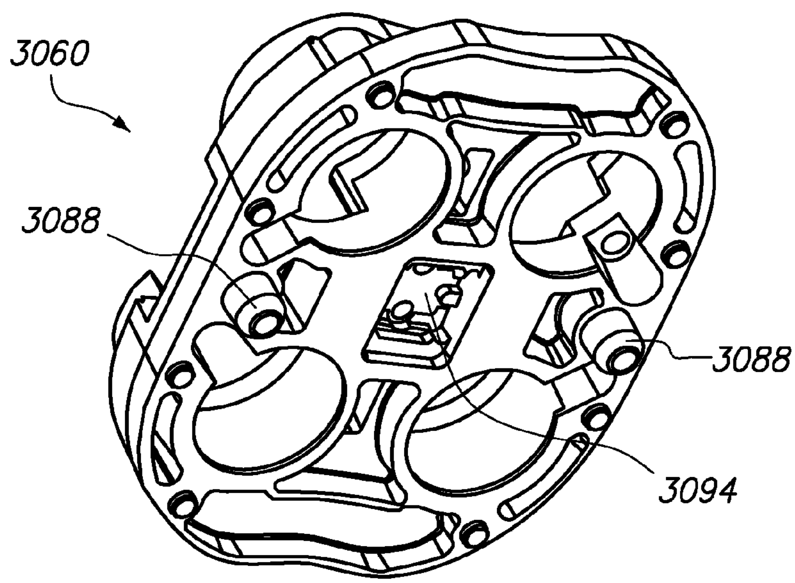


FIG. 139B

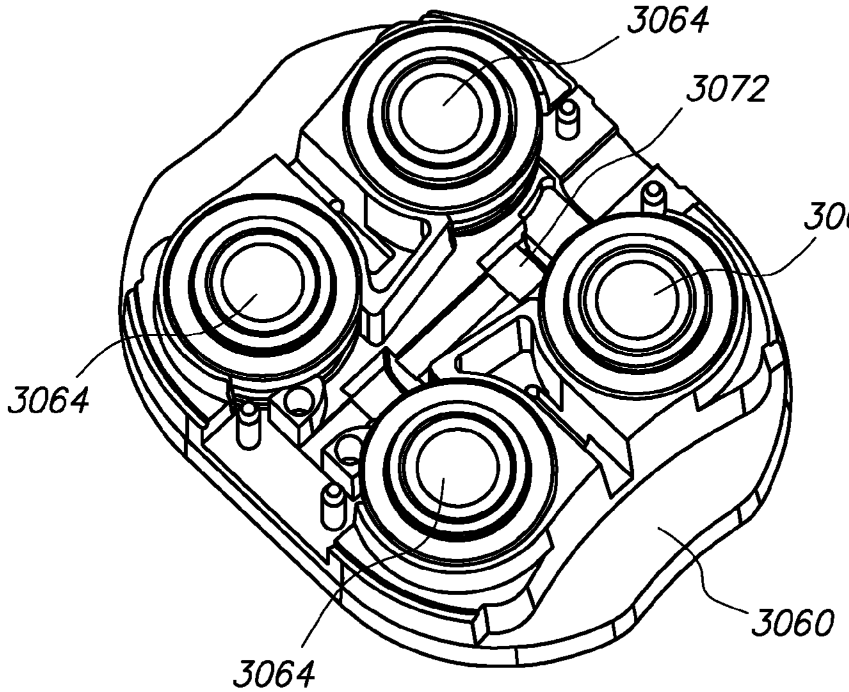


FIG. 140A

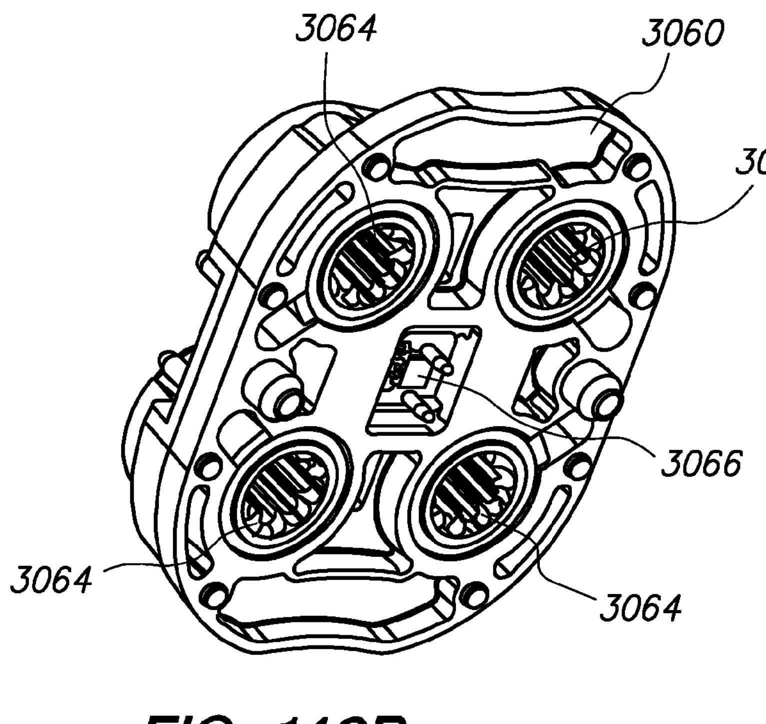


FIG. 140B

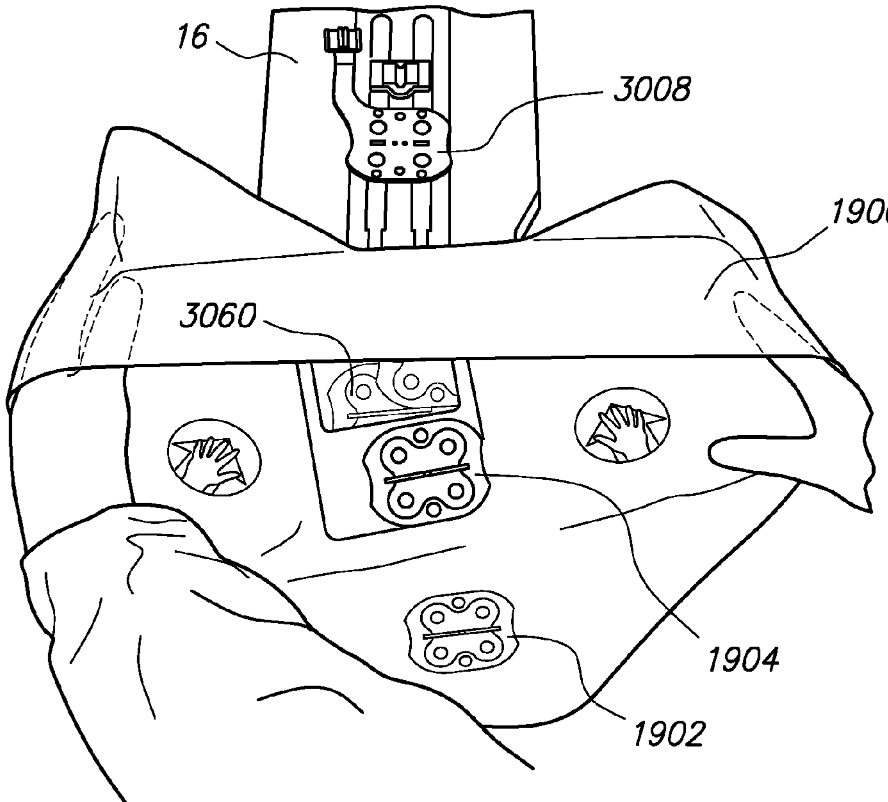


FIG. 141A

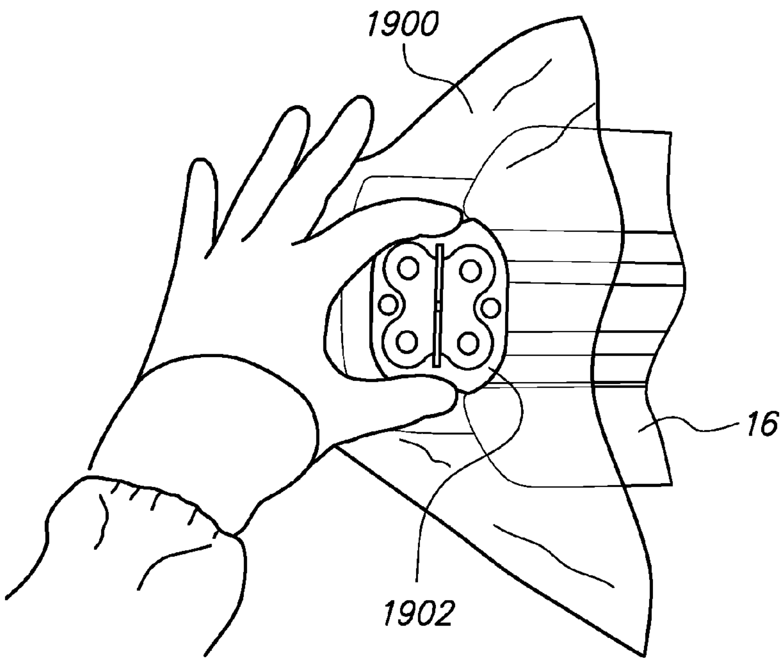


FIG. 141B

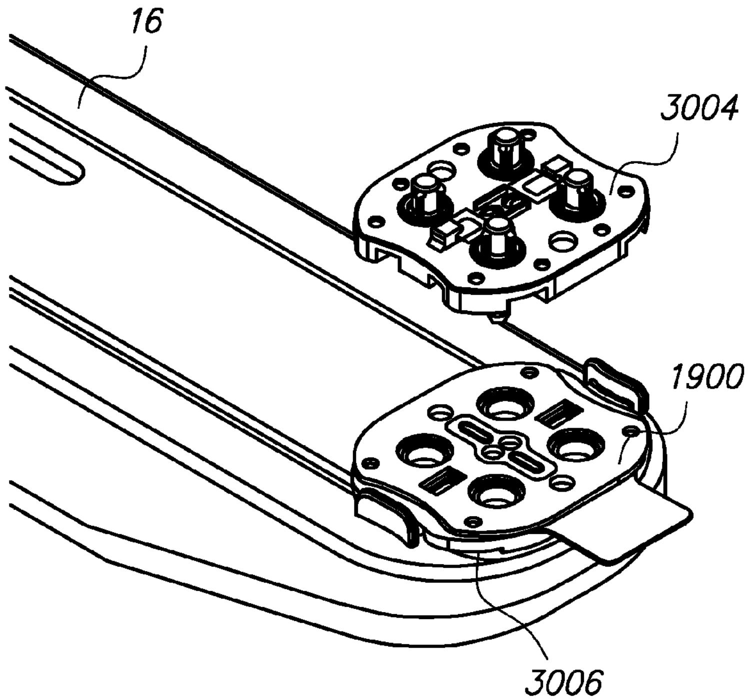


FIG. 142A

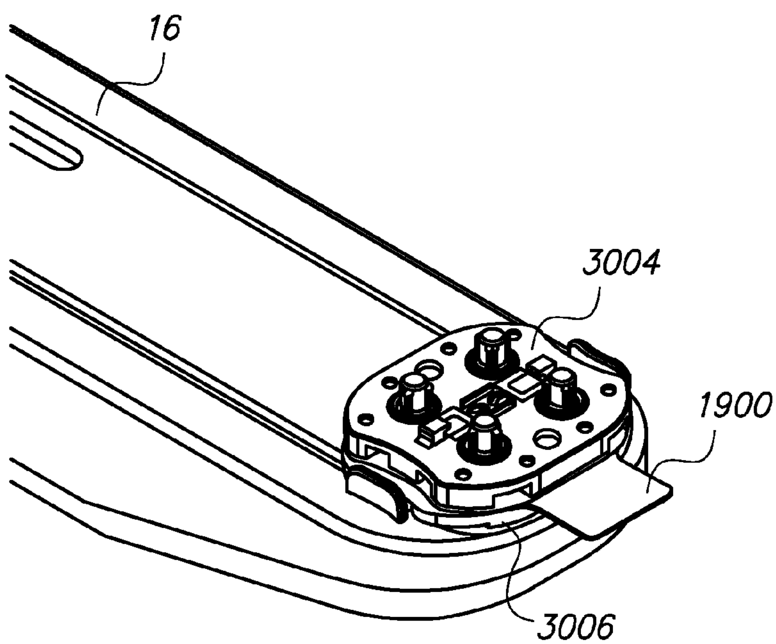


FIG. 142B

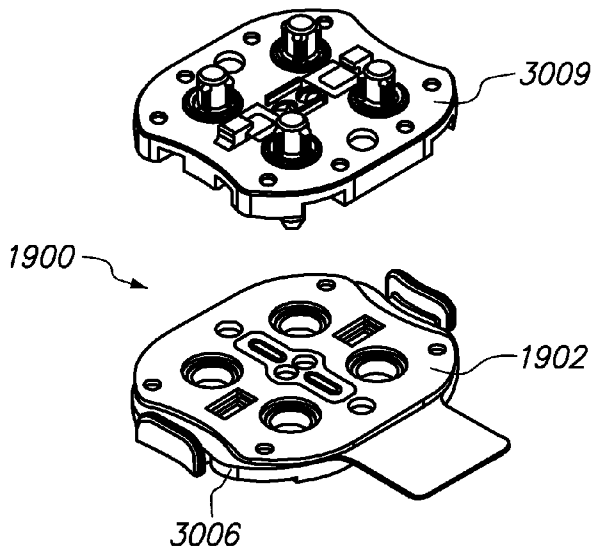


FIG. 143A

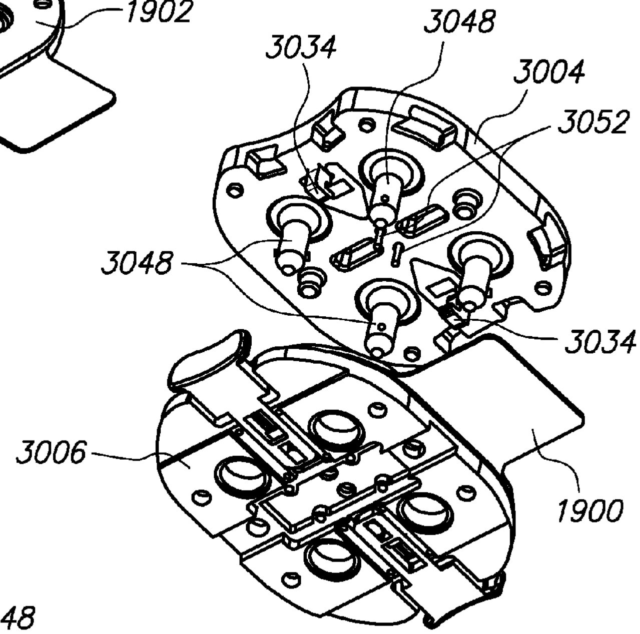


FIG. 143B

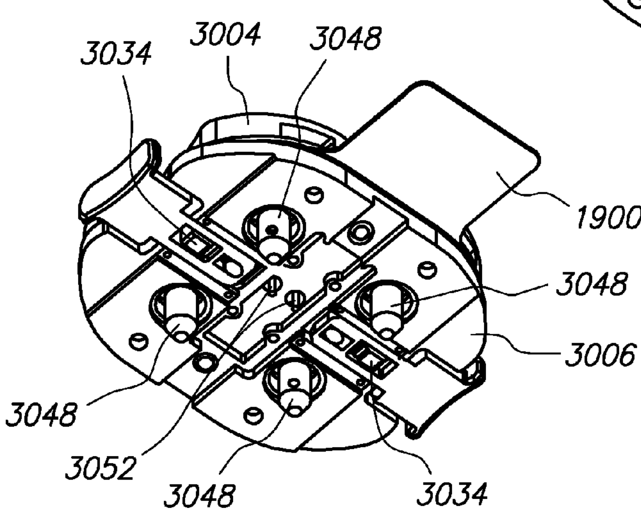


FIG. 143C

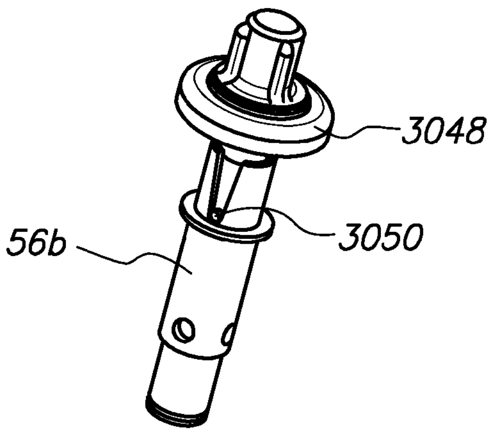


FIG. 144A

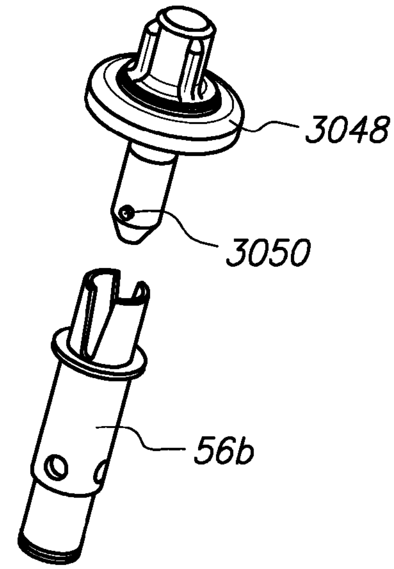


FIG. 144B

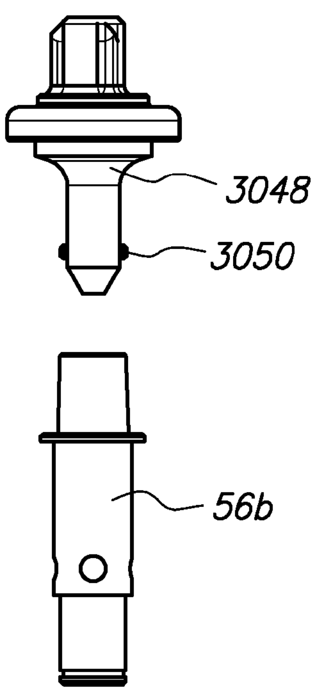


FIG. 144C

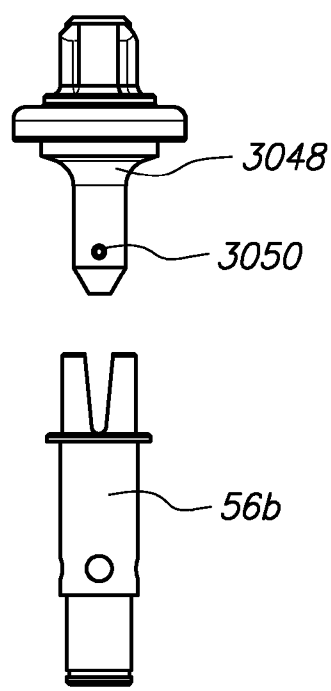


FIG. 144D

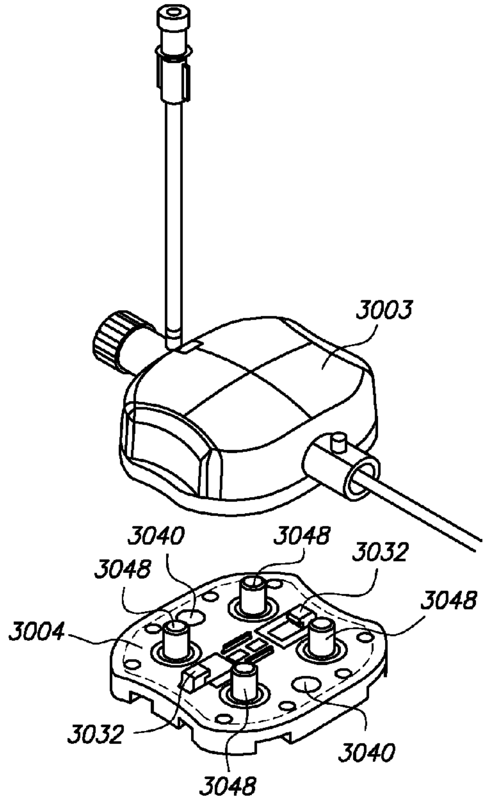


FIG. 145A

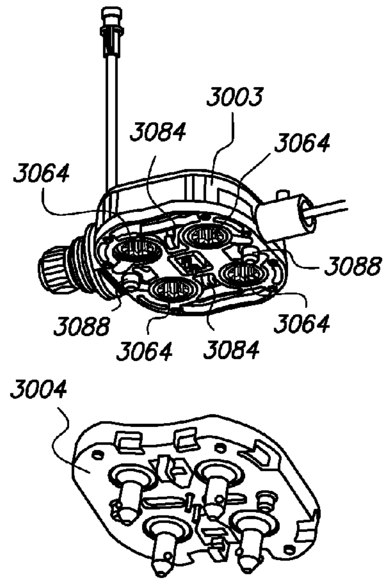


FIG. 145B

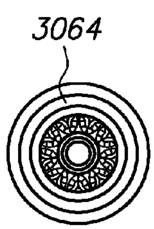


FIG. 146A

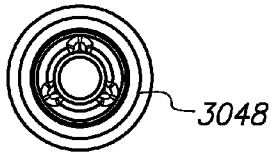


FIG. 146B

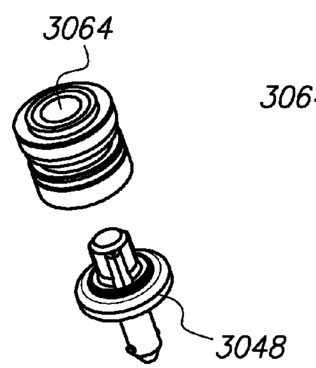


FIG. 147A

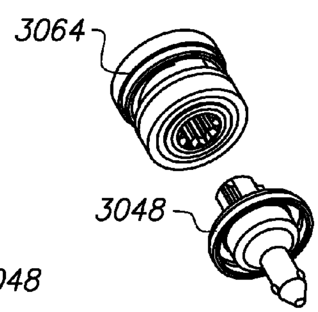


FIG. 147B

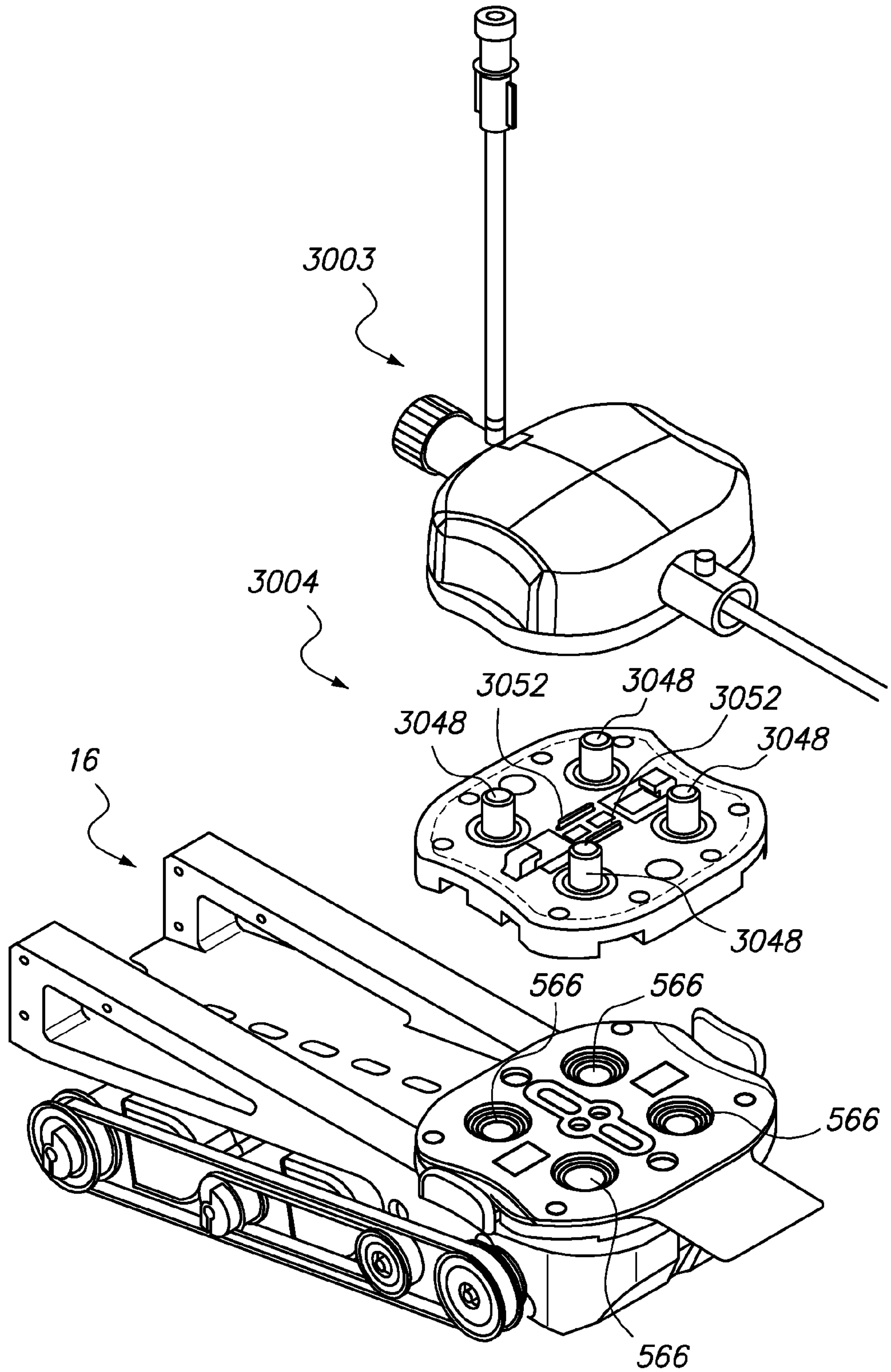
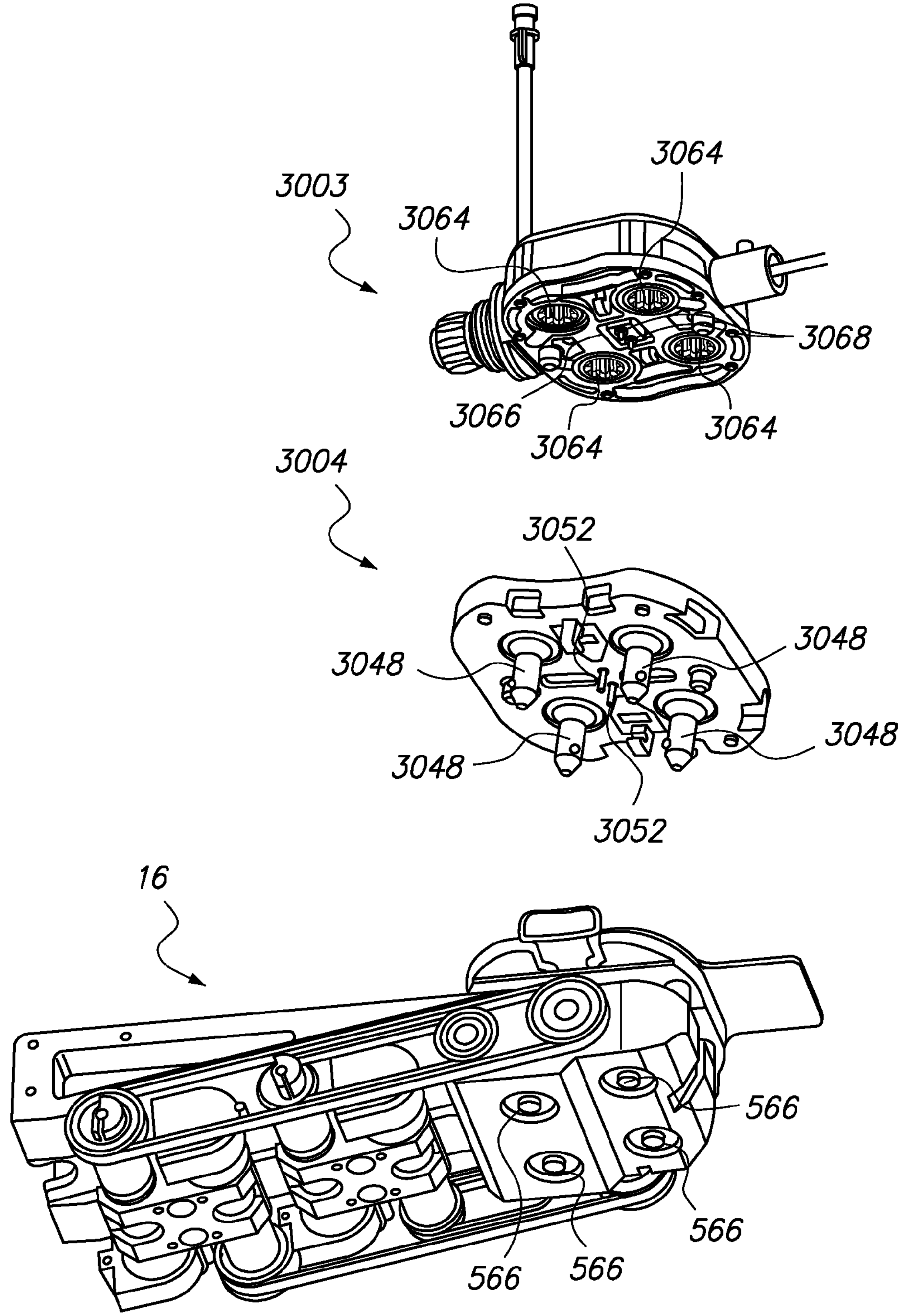


FIG. 148A


3003
3064
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3068
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3004
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FIG. 148B

SYSTEMS AND METHODS FOR MANIPULATING AN ELONGATE MEMBER

RELATED APPLICATION DATA

This application claims priority to and the benefit of U.S. Provisional Patent Application No. 61/384,220, filed Sep. 17, 2010, and U.S. Provisional Application No. 61/482,598, filed May 4, 2011, the entire disclosures of all of which are expressly incorporated by reference herein for all purposes.

This application is related to U.S. patent applications entitled "Steerable catheters," assigned Ser. No. 13/173,994 (issued as U.S. Pat. No. 8,827,948 on Sep. 9, 2014), "Robotic medical systems and methods," assigned Ser. No. 13/174,455 (now abandoned). "Systems and methods for positioning an elongate member inside a body," assigned Ser. No. 13/174,536, "Anti-buckling mechanisms and methods," assigned Ser. No. 13/174,563 (issued as U.S. Pat. No. 8,961,533 on Feb. 24, 2015), and "User interface and method for operating a robotic medical system," assigned Ser. No. 13/174,638 (now abandoned), all filed on Jun. 30, 2011.

INCORPORATION BY REFERENCE

All of the following U.S. patent applications are expressly incorporated by reference herein for all purposes:

U.S. patent application Ser. No. 11/179,007, filed on Jul. 6, 2005,
U.S. patent application Ser. No. 12/079,500, filed on Mar. 26, 2008,
U.S. patent application Ser. No. 11/678,001, filed on Feb. 22, 2007,
U.S. Patent Application No. 60/801,355, filed on May 17, 2006,
U.S. patent application Ser. No. 11/804,585, filed on May 17, 2007,
U.S. patent application Ser. No. 11/640,099, filed on Dec. 14, 2006,
U.S. patent application Ser. No. 12/507,727, filed on Jul. 22, 2009,
U.S. patent application Ser. No. 12/106,254, filed on Apr. 18, 2008,
U.S. patent application Ser. No. 12/192,033, filed on Aug. 14, 2008,
U.S. patent application Ser. No. 12/236,478, filed on Sep. 23, 2008,
U.S. patent application Ser. No. 12/833,935, filed on Jul. 9, 2010,
U.S. patent application Ser. No. 12/822,876, filed on Jun. 24, 2010, and
U.S. patent application Ser. No. 12/614,349, filed on Nov. 6, 2009

FIELD

The application relates generally to robotically controlled surgical systems, and more particularly to flexible instruments and instrument drivers that are responsive to a master controller for performing surgical procedures.

BACKGROUND

Robotic surgical systems and devices are well suited for use in performing minimally invasive medical procedures, as opposed to conventional techniques wherein the patient's body cavity is open to permit the surgeon's hands access to internal organs. For example, there is a need for a highly controllable yet minimally sized system to facilitate imaging, diagnosis, and treatment of tissues which may lie deep within a patient, and which may be preferably accessed only via naturally-occurring pathways such as blood vessels or the gastrointestinal tract.

SUMMARY

The subject application describes, among other things, a robotic system for controlling an elongate instrument. By means of non-limiting examples, the elongate instrument may include a catheter and a sheath surrounding at least a part of the catheter or other flexible and elongated medical instruments. In some embodiments, the sheath may be consider a catheter itself. Also, in other embodiments, the elongate instrument may optionally further include a guidewire that is at least partially surrounded by the catheter.

The elongate instrument may have different configurations in different embodiments. In accordance with some embodiments, an elongated medical device includes an elongated body having a proximal section, a distal section, and a working lumen extending through the proximal and distal sections, a first coil having a distal portion, and a proximal portion, the proximal portion of the first coil being slidable relative to the proximal section of the elongated body, and being closer to a wall of the elongated body than to an axis of the elongated body, wherein a lengthwise portion of the distal portion of the first coil is anchored to the distal section of the elongated body, and a first steering wire located within a lumen of the first coil. By means of non-limiting examples, the elongated medical device may be a catheter, a sheath, or any medical instrument having a working lumen. In one or more of the embodiments described herein, the working lumen may have a cross sectional area that is at least 30% of a cross sectional area of the elongated body. In one or more of the embodiments described herein, the lengthwise portion may be at least 10 mm. Also, in one or more of the embodiments described herein, the lengthwise portion may be at least 5% of an entire length of the first coil. In one or more of the embodiments described herein, the elongated body may have a proximal tip, and the proximal portion of the first coil may have a proximal tip that is proximal to the proximal tip of the elongated body.

The elongated medical device may have a variety of different configurations in different embodiments. In one or more of the embodiments described herein, the first coil may be anchored to the elongated body at a transition location between the proximal and distal sections of the elongated body. In one or more of the embodiments described herein, a loop at the distal portion of the first coil may be embedded into a wall of the distal section of the elongated body.

Also, in some embodiments described herein, the device may include a second coil having a distal portion anchored to the distal section of the elongated body, and a proximal portion slidable relative to the proximal section of the elongated body, and a second steering wire located within a lumen of the second coil. The steering wires allow the device to be steered in different directions during use.

The device may be mechanically driven in some embodiments. For example, in one or more of the embodiments described herein, the device may include a drivable instrument coupled to a proximal end of the elongated body and to the first and second steering wires, wherein the drivable instrument is configured to apply tension to the first and second steering wires. Also, in one or more of the embodiments described herein, the device may include a processor coupled to the drivable instrument, the processor configured

to receive a user command and generate a control signal based on the user command to control the drivable instrument.

The device may also optionally include other features in different embodiments. For example, in one or more of the embodiments described herein, the device may include first and second hypotubes fixedly secured to the drivable instrument, wherein the proximal portion of the first coil is secured to the first hypotube, and the proximal portion of the second coil is secured to the second hypotube. Also, in one or more of the embodiments described herein, the device may include a liner surrounding the proximal portion of the first coil, wherein the first coil is slidable relative to the liner.

In some embodiments, the elongated body may be a body of a catheter, a guidewire, or another elongated device. In such cases, the device may include an additional elongated body that is movably disposed around at least a part of the elongated body. The additional elongated body may be another catheter, a sheath, or another elongated device.

In some embodiments, the elongated medical device may have a steerable distal section and a proximal section that remains very flexible even while the distal section is being steered. Also, one or more of the embodiments described herein, the first coil and the first steering wire may be configured to maintain a bent configuration for the distal section of the elongated body, while allowing the proximal section of the elongated body to remain flexible.

The elongate instrument may have other configurations in other embodiments. For example, in accordance with other embodiments, an elongated medical device includes an elongated body having a proximal section, a distal section, and a working lumen extending through the proximal and distal sections, a first coil, wherein at least a lengthwise portion of the first coil is anchored to the distal section of the elongated body, a second coil in the proximal section of the elongated body that is slidable relative to the proximal section of the elongated body, wherein the second coil is axially aligned with the first coil along a length of the elongated body, and a steering wire located within a lumen of the first coil and within a lumen of the second coil. In one or more of the embodiments described herein, the lengthwise portion may be at least 10 mm. Also, in one or more of the embodiments described herein, the lengthwise portion may be at least 5% of a combined length of the first coil and the second coil. In one or more of the embodiments described herein, the first coil may be embedded within a wall of the elongated body. Also, in one or more of the embodiments described herein, a distal end of the second coil may be anchored to the elongate body at a location in which there is a transition between the first and second coils. In some embodiments, each of the first coil and the second coil may have an open pitch. In other embodiments, each of the first coil and the second coil may have a closed pitch. In further embodiments, the first coil may have an open pitch, and the second coil may have a closed pitch. In some embodiments, the first coil, the second coil, and the steering wire may be configured to maintain a bent configuration for the distal section of the elongated body, while allowing the proximal section of the elongated body to remain flexible. Also, in one or more of the embodiments described herein, the elongated body may have a proximal tip, and the second coil may have a proximal tip that is proximal to the proximal tip of the elongated body.

The device may be mechanically driven in some embodiments. For example, in some embodiments, the device may include a drivable instrument coupled to a proximal end of the elongated body and to the steering wire, wherein the drivable instrument is configured to apply tension to the steering wire. Also, in some embodiments, the device may include a processor coupled to the drivable instrument, the processor configured to receive a user command and generate a control signal based on the user command to control the drivable instrument.

The device may optionally include other features in other embodiments. For example, in one or more of the embodiments described herein, the device may include a hypotube fixedly secured to the drivable instrument, wherein a proximal portion of the second coil is secured to the hypotube. Also, in one or more of the embodiments described herein, the device may include a liner surrounding the second coil, wherein the second coil is slidable relative to the liner.

In some embodiments, the elongated body may be a body of a catheter, a guidewire, or another elongated device. In such cases, the device may include an additional elongated body that is movably disposed around at least a part of the elongated body.

Embodiments of the elongated medical device described herein may be used to perform different procedures in different embodiments. In accordance with some embodiments, a method performed using an elongated medical device includes providing the elongated medical device having an elongated body having a proximal section, a distal section, and a working lumen extending through the proximal and distal sections, a fist coil having a distal portion and a proximal portion, and a first steering wire located within a lumen of the first coil, and applying tension to the first steering wire, while allowing the proximal portion of the first coil to slide relative to the proximal section of the elongated body, wherein while the tension is being applied to the first steering wire, a lengthwise portion of the distal portion of the first coil is prevented from being moved relative to the distal section of the elongated body. In one or more of the embodiments described herein, the lengthwise portion may be at least 10 mm. Also, in one or more of the embodiments described herein, the lengthwise portion may be at least 5% of an entire length of the first coil. In one or more of the embodiments described herein, the elongated medical device may further include a second coil having a distal portion anchored to the distal section of the elongated body, and a proximal portion slidable relative to the proximal section of the elongated body, and a second steering wire located within a lumen of the second coil.

During the method, in some embodiments, the first coil may be prevented from being moved relative to the elongated body at a first region that is distal to a transition location between the proximal and distal sections of the elongated body, and may be allowed to slide relative to the elongated body at a second region that is proximal to the transition location. Also, in other embodiments, the lengthwise portion of the distal portion of the first coil may be prevented from being moved by embedding a loop at the distal portion of the first coil into a wall of the distal section of the elongated body.

The method may be performed using a robotic system in some embodiments. For example, in some embodiments, the tension may be applied using a drivable instrument. Also, in one or more of the embodiments described herein, the method may include generating a control signal by a processor based on a user command received by the processor, wherein the drivable instrument applies the tension to the first steering wire in response to the control signal.

In one or more of the embodiments described herein, the tension may be applied to steer the distal section of the elongated body while steering force may be isolated from the proximal section of the elongated body. Also, in some embodiments described herein, the tension may be applied to steer the distal section while a bending stiffness of the proximal section of the elongated body is not significantly affected. In still further embodiments, the tension may be applied to steer the distal section of the elongated body without creating unwanted curvature at the proximal section of the elongated body. In other embodiments described herein, the tension may be applied to steer the distal section of the elongated body while a shape of the proximal section of the elongated body is unaffected by the steering of the distal section.

The elongate instrument that may be used with the robotic system may have other configurations in other embodiments. For example, in accordance with other embodiments, an elongated medical device includes an elongated body having a proximal section, a distal section, and a working lumen extending through the proximal and distal sections, wherein the distal section has a tapered profile, a first coil having a distal portion anchored to the distal section of the elongated body, and a proximal portion slidable relative to the proximal section of the elongated body, a first steering wire located within a lumen of the first coil, a second coil having a distal portion anchored to the distal section of the elongated body, a second steering wire located within a lumen of the second coil, a control ring located at the distal section of the elongated body, and a spine located in the elongated body, wherein the first coil and the second coil are located radially away from an axis of the spine. In one or more of the embodiments described herein, the working lumen may have a tapered configuration. Also, in one or more of the embodiments described herein, the device may include a drivable instrument coupled to a proximal end of the elongated body and to the first and second steering wires, wherein the drivable instrument is configured to apply tension to the first and second steering wires. In one or more of the embodiments described herein, the device may include a processor coupled to the drivable instrument, the processor configured to receive a user command and generate a control signal based on the user command to control the drivable instrument.

The robotic system may control the elongate instrument in different configurations. In accordance with some embodiments, a robotic surgical system includes a flexible elongated member, a first member movably disposed around at least a portion of the flexible elongated member, a second member movably disposed around at least a portion of the first member, a drive assembly coupled to each of the flexible elongated member, the first member, and the second member, and a control interface for receiving an input command from a user, wherein the drive assembly is configured to automatically move one or both of the first member and the second member while maintaining the flexible elongated member at a fixed axial position in response to the received input command.

In some embodiments, the drive assembly may be configured to move the first member distally, without moving the second member, while maintaining the flexible elongated member at the fixed position, in response to the received input command. Also, in some embodiments, the drive assembly may be configured to move the first member proximally, without moving the second member, while maintaining the flexible elongated member at the fixed position, in response to the received input command. In other embodiments, the drive assembly may be configured to move the second member distally, without moving the first member, while maintaining the flexible elongated member at the fixed position, in response to the received input command. In further embodiments, the drive assembly may be configured to move the second member proximally, without moving the first member, while maintaining the flexible elongated member at the fixed position, in response to the received input command. In still further embodiments, the drive assembly may be configured to move each of the first member and the second member distally, while maintaining the flexible elongated member at the fixed position, in response to the received input command. In other embodiments, the drive assembly may be configured to move each of the first member and the second member proximally, while maintaining the flexible elongated member at the fixed position, in response to the received input command.

In one or more of the embodiments described herein, the first member may include a first pull wire, and wherein the drive assembly may be further configured to adjust a tension in the first pull wire. In some embodiments, the drive assembly may be configured to move the first member proximally relative to the second member after releasing at least some tension in the first pull wire, while maintaining the flexible elongated member at the fixed position, in response to the received input command. In other embodiments, the second member may include a second pull wire, and wherein the drive assembly may be further configured to adjust a tension in the second pull wire. In further embodiments, the drive assembly may be configured to move each of the first member and the second member proximally relative to the flexible elongated member after releasing at least some tension in the second pull wire, while maintaining the flexible elongated member at the fixed position, in response to the received input command. Also, in some embodiments, the drive assembly may be configured to translate and/or rotate the flexible elongated member.

In some embodiments, the flexible elongated member may include a guidewire. In one or more of the embodiments described herein, the guidewire may have a preformed configuration. Also, in one or more of the embodiments described herein, the system may include a mechanism for controlling and/or maintaining the preformed configuration.

In accordance with other embodiments, a robotic surgical system includes a member having a first controllable section and a second controllable section distal of the second controllable section, a drive assembly coupled to the tubular member, and a control interface for allowing a user to select one of the first and second controllable sections of the tubular member to move, wherein the drive assembly is configured to independently move the first controllable section or the second controllable section in response to an input command from the user received at the control interface. In one or more of the embodiments described herein, the first controllable section and the second controllable section may be in a telescopic configuration. In some embodiments, the drive assembly may be configured to move the first controllable section while maintaining the second controllable section in a fixed position. Also, in some embodiments, the first controllable section may have a bent configuration, and the drive assembly may be configured to move the second controllable section while maintaining the bent configuration for the first controllable section. In some embodiments, the system may include a flexible elongated member disposed inside the tubular member, wherein the drive assembly is configured to move the member while maintaining the flexible elongated member at a fixed position. Also, in other embodiments, the drive assembly may be configured to translate and/or rotate the flexible elongated member.

In some embodiments, the flexible elongated member may include a guidewire. In one or more of the embodiments described herein, the guidewire may have a preformed configuration. Also, in one or more of the embodiments described herein, the system may include a mechanism for controlling and/or maintaining the preformed configuration.

The robotic surgical system may have other configurations in other embodiments. For example, in accordance with other embodiments, a robotic surgical system includes an elongate member having a pre-shaped configuration, a member disposed over the elongate member, a drive assembly coupled to the elongate member and the member, and a control interface for receiving an input command from a user, wherein the drive assembly is configured to move the member distally relative to the elongate member along the pre-shaped configuration of the elongate member in response to the input command received at the control interface.

In some embodiments, the elongate member may include a flexible elongated member. In one or more of the embodiments described herein, the flexible elongated member may include a guidewire. Also, in some embodiments, the drive assembly may be configured to translate and/or rotate the guidewire. In other embodiments, the elongate member may have a tubular configuration. In one or more of the embodiments described herein, the tubular member may include a pull wire located in a wall thereof, and wherein the drive assembly may be configured to adjust a tension in the pull wire before moving the tubular member distally relative to the elongate member.

Also, in other embodiments, the robotic system may control two elongate members of an elongate instrument in a telescopic fashion to thereby advance the elongate instrument inside a body. For example, in accordance with some embodiments, a robotic method includes positioning a flexible elongated member that has a preformed configuration, wherein at least a part of the flexible elongated member has a first member disposed around it, and wherein the first member includes a first wire for bending the first member or for maintaining the first member in a bent configuration, releasing at least some tension in the first wire to relax the first member, and advancing the first member distally relative to the flexible elongated member while the first member is in a relaxed configuration. In some embodiments, the act of positioning the flexible elongated member may include advancing the flexible elongated member. Also, in some embodiments, the act of positioning the flexible elongated member may include using a drive mechanism. In some embodiments, the first member may include a tubular member. Also, in some embodiments, the flexible elongated member may include a guidewire. In one or more of the embodiments described herein, the guidewire may have a preformed configuration. In other embodiments, the act of positioning may include advancing and/or rotating the flexible elongated member.

In other embodiments, the method may include re-tensioning the first wire to stiffen the first member. Also, in other embodiments, the method may include repeating the acts of releasing at least some tension and advancing the first member. In still further embodiments, at least a part of the first member may have a second member disposed around it, and wherein the second member may include a second wire for bending the second member or for maintaining the second member in a bent configuration, and the method may include releasing at least some tension in the second wire to relax the second member, and advancing the second member distally relative to the flexible elongated member while the second member is in a relaxed configuration.

In some embodiments, the acts of advancing the first member and the second member may be performed simultaneously so that both the first member and the second member are advanced together. In other embodiments, the first member may be advanced before the second member. In further embodiments, the method may include re-tensioning the first wire to stiffen the first member, and re-tensioning the second wire to stiffen the second member. In still further embodiments, the first member may be advanced until a distal end of the first member has passed through an opening in a body.

The method may be performed using a drivable instrument in accordance with some embodiments. For example, in some embodiments, the first wire may be coupled to a drivable instrument, and wherein the at least some tension in the first wire may be released by the drivable instrument in response to a control signal received from a processor. Also, in some embodiments, the first member may be coupled to a drivable instrument, and wherein the first member may be advanced by the drivable instrument in response to a control signal received from a processor.

In accordance with other embodiments, a robotic method includes rolling a first member, wherein the first member is disposed around a flexible elongated member, positioning the flexible elongated member to compensate for the rolling of the first member. In one or more of the embodiments described herein, the act of rolling the first member may include rotating the first member about its longitudinal axis. In one or more of the embodiments described herein, the act of rolling the first member may include bending the first member in different radial directions to create an artificial rolling.

In accordance with other embodiments, a robotic system includes a flexible elongated member that has a preformed configuration, a first member disposed around at least a part of the flexible elongated member, wherein the first member includes a first wire, a drive assembly configured to position the flexible elongated member, a first drive mechanism configured to manipulate the first wire to bend the first member or to maintain the first member in a bent configuration, a second drive mechanism configured to move the first member relative to the flexible elongated member, and a controller coupled to the first drive mechanism and the second drive mechanism, wherein the controller is configured to transmit first control signals to operate the first drive mechanism so that the first drive mechanism releases at least some tension in the first wire to relax the first member, and to operate the second drive mechanism to advance the first member distally relative to the flexible elongated member while the first member is in a relaxed configuration. In some embodiments, the drive assembly may be configured to advance the flexible elongated member distally relative to the first member. In other embodiments, the controller may be configured to operate the first drive mechanism to re-tension the first wire to stiffen the first member after the first member is relaxed. Also, in other embodiments, the controller may be configured to operate the first and second drive mechanisms to repeat the acts of releasing at least some tension and advancing the first member.

In one or more of the embodiments described herein, the system may include a second member disposed around at least a part of the first member, wherein the second member includes a second wire, a third drive mechanism configured to manipulate the second wire to bend the second member or to maintain the second member in a bent configuration, and a fourth drive mechanism configured to move the second member, wherein the controller may be further configured to transmit second control signals to operate the third drive mechanism to release at least some tension in the second wire to relax the second member, and to operate the fourth drive mechanism to advance the second member distally relative to the flexible elongated member while the second member is in a relaxed configuration. In some embodiments, the controller may be configured to control the second drive mechanism and the fourth drive mechanism to advance the first member and the second member together and simultaneously. In other embodiments, the controller may be configured to cause the first member to be advanced before the second member. In further embodiments, the controller may be configured to operate the first drive mechanism to re-tension the first wire to stiffen the first member, and to operate the third drive mechanism to re-tension the second wire to stiffen the second member.

Embodiments of the system described herein may be used to perform various methods in different embodiments. In accordance with some embodiments, a robotic method includes inserting a first elongate member and a second elongate member into a body, wherein the second elongate member is slidably disposed around at least a portion of the first elongate member, applying tension to one or more steering wires in the first elongate member to bend a distal portion of the first elongate member, maintaining the applied tension so that the bent distal portion of the first elongate member stays stiffened, and advancing the second elongate member distally relative to the first elongate member while using the stiffened distal portion of the first elongate member as a first guide to direct the second elongate member. In some embodiments, the method may also include releasing at least some tension in one or more steering wires in the second elongate member to un-stiffen the second elongate member before the act of advancing. In some embodiments, the first elongate member may include a catheter, and the second elongate member may include a sheath. Also, in some embodiments, the second elongate member may not include any steering wire.

In one or more of the embodiments described herein, after the act of advancing, the method may include releasing at least some tension in the one or more steering wires in the first elongate member to un-stiffen the first elongate member, applying tension to one or more steering wires in the second elongate member to bend a distal portion of the second elongate member, maintaining the applied tension in the one or more steering wires in the second elongate member so that the bent distal portion of the second elongate member stays stiffened, and advancing the first elongate member distally relative to the second elongate member while using the stiffened distal portion of the second elongate member as a second guide to direct the first elongate member

In some embodiments, the method may include adjusting the applied tension. In one or more of the embodiments described herein, the applied tension may be adjusted automatically. Also, in one or more of the embodiments described herein, the tension may be adjusted to maintain the distal portion of the first elongate member in a desired bent configuration.

The robotic system may also optionally include an anti-buckling device for supporting the elongate instrument as the elongate instrument is being advanced into the body in accordance with some embodiments. Such feature may prevent the elongate instrument from buckling.

One or more of the embodiments of the robotic system described herein may optionally further include a mechanism for preventing buckling of the elongate instrument. For example, in accordance with some embodiments, an anti-buckling device includes a first coupler for coupling to a first device, a second coupler for coupling to a second device that is configured to position a catheter member, a first set of support members coupled between the first coupler and the second coupler, and a plurality of holders coupled to the support members, the holders configured for supporting the catheter member, wherein the first set of support members form a support frame that can be extended by moving the first and second couplers away from each other, and can be collapsed by moving the first and second couplers towards each other. In some embodiments, the first set of support members may form a planar configuration. Also, in some embodiments, the device may further include a second set of support members that are disposed next to the first set of support members. In one or more of the embodiments described herein, the second set of support members may be configured to maintain the holders in a same orientation relative to each other, wherein the orientation may be perpendicular to a longitudinal axis of the catheter member. In further embodiments, the device may include a third set of support members that are disposed between the first and second sets of support members. In one or more of the embodiments described herein, the third set of support members may be configured to maintain the holders in a same orientation relative to each other. Also, in some embodiments, the support members may be arranged in a scissor-like configuration. In one or more of the embodiments described herein, the first set of support members may be configured to provide a variable buckling resistance for the catheter member supported by the support members in response to an advancement of the catheter member. In some embodiments, the first device may include a stabilizer that is configured to be attached to a patient. Also, in some embodiments, the first device may include a first driver and the second device comprises a second driver.

The holders in the anti-buckling device may have different features in different embodiments. For example, in one or more of the embodiments described herein, each of the holders may have an opening for accommodating a portion of the catheter member supported by the holders. Also, in one or more of the embodiments described herein, the holders may be moveable relative to a catheter member supported by the holders in a manner such that the holders are maintained at a substantially equal distance from one another as they are moved.

Other devices for supporting an elongate member are also described herein. For example, in accordance with other embodiments, a support device includes a first set of support members arranged in a scissor-like configuration to form a support frame, wherein the support frame has a first end and a second end, and can be extended by moving the first and second ends away from each other, or collapsed by moving the first and second ends towards each other, and a plurality of holders coupled to the support members, the holders configured for supporting a catheter member, wherein the holders are moveable relative to the catheter member supported by the holders, such that the holders are maintained at a substantially same distance from one another regardless of a distance between the first and second ends of the support frame. In some embodiments, the device may include a first coupler disposed at the first end of the support frame for coupling to a driver that is configured to position a catheter member. Also, in some embodiments, the device may include a second coupler disposed at the second end of the support frame for coupling to a stabilizer that is configured to be attached to a patient. In one or more of the embodiments described herein, the device may include a second coupler disposed at the second end of the support frame for coupling to a driver. Also, in one or more of the embodiments described herein, the support members may form a scissor-like configuration. In some embodiments, each of the holders may have an opening for accommodating a portion of the catheter member supported by the holders. Also, in some embodiments, the support frame may be configured to provide a variable buckling resistance for the catheter member supported by the holders in response to an advancement of the catheter member.

In some embodiments, the device may include a second set of support members disposed next to the first set of support members. In one or more of the embodiments described herein, the second set of support members may be configured to maintain the holders in a same orientation relative to each other. In further embodiments, the device may include a third set of support members disposed between the first and second sets of support members. In one or more of the embodiments described herein, the third set of support members may be configured to maintain the holders in a same orientation relative to each other.

The anti-buckling device may have different configurations in different embodiments. For example, in accordance with other embodiments, an anti-buckling device includes a first coupler for coupling to a first device, a second coupler for coupling to a second device, a first set of support members disposed between the first and second couplers, wherein the first set of support members are arranged in a scissor-like configuration, and a plurality of holders coupled to the first set of support members, the holders configured for supporting an elongated medical device. In some embodiments, the elongated medical device may include a catheter member, an endoscope, or an ablation device. Also, in some embodiments, the first set of support members may be configured to provide a variable buckling resistance for the elongated medical device being supported by the holders in response to an advancement of the elongated medical device.

Devices having other configurations that are configured to support an elongate instrument are also described herein. For example, in accordance with other embodiments, a support system includes a first elongated member with a lumen, a second elongated member slidably disposed within the lumen of the first elongated member, a first anti-buckling device configured to support the first elongated member, and a second anti-buckling device configured to support the second elongated member. In some embodiments, the first elongated member may include a sheath, and the second elongated member comprises a catheter. Also, in some embodiments, the first anti-buckling device may include support members arranged in a scissor-like configuration. In one or more of the embodiments described herein, the support members may include telescoping tubes. Also, in one or more of the embodiments described herein, the first anti-buckling device may have a first end configured to detachably couple to a first drive assembly, and a second end configured to detachably couple to a patient. In one or more of the embodiments described herein, the second anti-buckling device may have a first end configured to detachably couple to a second drive assembly, and a second end configured to detachably couple to the first drive assembly.

The support system may have different configurations in different embodiments. For example, in accordance with other embodiments, a support system includes a catheter having a first end for insertion into a patient, and a second end for coupling to a first drive assembly, and a first anti-buckling device configured to laterally support the catheter as the first end of the catheter is being advanced distally by the first drive assembly. In some embodiments, the system may include a sheath with a first end for insertion into the patient, a second end for coupling to a second drive assembly, and a lumen in which the catheter is slidably disposed, and a second anti-buckling device configured to laterally support the sheath as the sheath is being advanced by the second drive assembly. Also, in some embodiments described herein, the system may include the first drive assembly and the second drive assembly. In one or more of the embodiments described herein, the first anti-buckling device may have a first end configured to detachably couple to the first drive assembly, and a second end configured to detachably couple to the second drive assembly. Also, in one or more of the embodiments described herein, the second anti-buckling device may have a first end configured to detachably couple to the second drive assembly, and a second end configured to detachably couple to the patient. In one or more of the embodiments described herein, the first anti-buckling device may include support members arranged in a scissor-like configuration.

Embodiments of the anti-buckling/support device may be used to perform different methods in different embodiments. For example, in accordance with some embodiments, a method includes advancing a first flexible elongated member distally relative to a patient, and laterally supporting at least a part of the first flexible elongated member using a first anti-buckling device to prevent the first flexible elongated member from buckling during the act of advancing. In some embodiments, the act of laterally supporting at least a part of the first flexible elongated member may include providing a plurality of lateral supports along a length of the first flexible elongated member, and wherein the lateral supports may be slidable relative to the first flexible elongated member. Also, in some embodiments, the method may include changing a spacing of the lateral supports in response to the act of advancing. In other embodiments, the method may include advancing a second flexible elongated member distally relative to the patient, the second flexible elongated member disposed circumferentially around the first flexible elongated member, and laterally supporting at least a part of the second flexible elongated member using a second anti-buckling device to prevent the second flexible elongated member from buckling during the act of advancing the second flexible elongated member. In one or more of the embodiments described herein, the first flexible elongated member may include a catheter.

The robotic system may also optionally include a manipulator for manipulating an elongate member, such as a guidewire, in accordance with some embodiments. For example, in accordance with some embodiments, an elongate member manipulator includes an elongate member holder having first and second rotary members configured to hold an elongate member, wherein the rotary members are actuated in opposite rotational directions to generate a corresponding linear motion of the elongate member held by the rotary members along a longitudinal axis of the elongate member, and wherein the rotary members are actuated in opposite linear directions to generate a corresponding rotational motion of the elongate member held by the rotary members about the longitudinal axis of the elongate member. In some embodiments, the manipulator may include a drive assembly for actuation of the first and second rotary members, wherein the elongate member holder is releasably coupled to the drive assembly. Also, in some embodiments, the manipulator may include a sterile barrier positioned between the drive assembly and the elongate member holder, wherein the drive assembly is configured to transfer rotational motion across the sterile barrier to the rotary members to generate the corresponding linear motion of the elongate member along the longitudinal axis of the elongate member. In other embodiments, the manipulator may include a sterile barrier positioned between the drive assembly and the elongate member holder, wherein the drive assembly is configured to transfer linear motion across the sterile barrier to the rotary members to generate the corresponding rotational motion of the elongate member about the longitudinal axis of the elongate member.

In one or more of the embodiments described herein, the drive assembly may be configured to actuate the rotary members in rotational and linear directions simultaneously. Also, in one or more of the embodiments described herein, the rotary members may be actuated in the rotational and linear directions at different respective rates. Also, in one or more of the embodiments described herein, the drive assembly may be configured to provide rotational actuation and linear actuation for the rotary members separately, and wherein the rotary members may be configured to maintain engagement with the elongate member between the rotational actuation and linear actuation of the rotary members.

In some embodiments, the elongate member may include a guide wire. Also, in some embodiments, the first and second rotary members may include first and second feed rollers. In one or more of the embodiments described herein, the first feed roller may have a groove cut around an outer diameter of the first feed roller, wherein the groove may be configured for receiving an elongate member. Also, in one or more of the embodiments described herein, the first feed roller may be motor driven and the second feed roller may be idle. In addition, in some embodiments, the first rotary member may include a first flexible member with a first engagement surface, and the second rotary member may include a second flexible member with a second engagement surface. Also, in some embodiments, the first rotary member may be motor driven and the second rotary member may be idle. In further embodiments, the manipulator may include an elongate member support configured to hold the elongate member and to prevent buckling of the elongate member during rotational or linear motion of the elongate member. Also, in some embodiments, the rotary members may include a first rotary member and a second rotary member, and the first rotary member is a first feed belt assembly comprising two or more belts with spacing between the belts to accommodate at least a portion of the elongate member support. In further embodiments, the second rotary member may include a second feed belt assembly comprising a belt wound around a plurality of pulleys to create a multiple segmented belt, the multiple segmented belt configured to contact the first feed belt assembly while providing clearance for a portion of the elongate member support extending between the belts of the first feed belt assembly. In one or more of the embodiments described herein, the first and second rotary members and the elongate member support may be arranged such that the elongate member can be held between the first and second rotary members while being supported by the elongate member support. Also, in one or more of the embodiments described herein, the elongate member support may have one or more protrusions with grooves, wherein the grooves may be configured to hold the elongate member to prevent buckling of the elongate member during rotational or linear motion of the elongate member, and the protrusions may be positioned within the spacing between the belts.

In some embodiments, the manipulator may include a roll support configured to position the elongate member so that a bend at the elongate member faces towards a first direction, and to position the elongate member so that the bend faces towards a second direction that is opposite from the first direction. In one or more of the embodiments described herein, the roll support may include a scissor jack. Also, in some embodiments, the manipulator may include a force sensor to measure force at a distal tip of the elongate member. In other embodiments, the manipulator may include one or more slip rollers for gripping the elongate member, wherein the slip rollers may be decoupled from the rotary members to detect sliding or slipping of the elongate member between the rotary members. In further embodiments, the manipulator may include a controller including a master input device, and an instrument driver in communication with the controller, the instrument driver configured to interface with a guide member and a sheath member.

In some embodiments, an elongate member manipulator may be implemented as a part of a robotic system. For example, in accordance with some embodiments, a robotic surgical system includes a controller including a master input device, an instrument driver in communication with the controller, the instrument driver configured to interface with an inner tubular member and an outer tubular member that surrounds at least a portion of the inner tubular member, and an elongate member manipulator comprising a drive assembly responsive to control signals generated, at least in part, by the master input device, and an elongate member holder releasably coupled to the drive assembly, the elongate member holder having first and second rotary members configured to hold an elongate member, wherein the drive assembly is configured to actuate the rotary members in opposite rotational directions to generate a corresponding linear motion of the elongate member along a longitudinal axis of the elongate member, wherein the drive assembly is configured to actuate said rotary members in opposite linear directions to generate a corresponding rotational motion of the elongate member about the longitudinal axis of the elongate member, and wherein the elongate member manipulator is configured to feed the elongate member into the inner tubular member. In some embodiments, the system may optionally further include a sterile barrier positioned between the drive assembly and the elongate member holder, wherein the drive assembly may be configured to transfer rotational motion across the sterile barrier to the rotary members to generate the corresponding linear motion of the elongate member along the longitudinal axis of the elongate member. Also, in some embodiments, the system may include a sterile barrier positioned between the drive assembly and the elongate member holder, wherein the drive assembly may transfer linear motion across the sterile barrier to the rotary members to generate the corresponding rotational motion of the elongate member about the longitudinal axis of the elongate member.

In some embodiments, the drive assembly may be configured to actuate the rotary members in rotational and linear directions simultaneously. Also, in some embodiments, the rotary members may be actuated in the rotational and linear directions at different respective rates. In one or more of the embodiments described herein, the drive assembly may be configured to provide rotational actuation and linear actuation for the rotary members separately, and wherein the rotary members may be configured to maintain engagement with the elongate member between the rotational actuation and linear actuation of the rotary members. In some embodiments, the elongate member may include a guide wire. Also, in some embodiments, the first and second rotary members may include first and second feed rollers. In one or more of the embodiments described herein, the first feed roller may have a groove cut around an outer diameter of the first feed roller, wherein the groove may be configured for receiving an elongate member. Also, in one or more of the embodiments described herein, the first feed roller may be motor driven and the second feed roller may be idle. In addition, in one or more of the embodiments described herein, the first rotary member may include a first flexible member with a first engagement surface, and the second rotary member may include a second flexible member with a second engagement surface. In other embodiments, the first flexible member may be motor driven and the second flexible member may be idle. In further embodiments, the system may include an elongate member support configured to hold the elongate member and to prevent buckling of the elongate member during rotational or linear motion of the elongate member. In still further embodiments, the rotary members may include a first rotary member and a second rotary member, and wherein the first rotary member comprises a first feed belt assembly comprising two or more belts with spacing between the belts to accommodate at least a portion of the elongate member support.

In some embodiments, the second rotary member may include a second feed belt assembly comprising a belt wound around a plurality of pulleys to create a multiple segmented belt, the multiple segmented belt configured to contact the first feed belt assembly while providing clearance for a portion of the elongate member support extending between the belts of the first feed belt assembly. Also, in some embodiments, the first and second rotary members and the elongate member support may be arranged such that the elongate member can be held between the first and second rotary members while being supported by the elongate member support. In one or more of the embodiments described herein, the elongate member support may have one or more protrusions with grooves, wherein the grooves are configured to hold the elongate member to prevent buckling of the elongate member during rotational or linear motion of the elongate member, and the protrusions are positioned within the spacing between the belts. In further embodiments, the system may optionally further include a roll support configured to position the elongate member so that a bend at the elongate member faces towards a first direction, and to position the elongate member so that the bend faces towards a second direction that is opposite from the first direction. In one or more of the embodiments described herein, the roll support may include a scissor jack. Also, in some embodiments, the system may include a force sensor to measure force at a distal tip of the elongate member. In further embodiments, the system may include one or more slip rollers for gripping the elongate member, wherein the slip rollers are decoupled from the rotary members to detect sliding or slipping of the elongate member between the rotary members.

Various methods for manipulating an elongate member are provided. For example, in accordance with some embodiments, a method of manipulating an elongate member in two degrees of freedom includes holding an elongate member between two rotary members, actuating the rotary members in opposite rotational directions to generate a corresponding linear motion of the elongate member along a longitudinal axis of the elongate member, and actuating the rotary members in opposite linear directions to generate a corresponding rotational motion of the elongate member about the longitudinal axis of the elongate member. In some embodiments, the rotary members may include feed belts. Also, in some embodiments, the acts of actuating may be performed simultaneously. In other embodiments, the acts of actuating may be performed at different respective rates. In still further embodiments, the acts of actuating may be performed separately, and wherein between the acts or actuating, the rotary members maintain engagement with the elongate member. In some embodiments, the method may optionally further include loading an elongate member by separating the two rotary members, and placing the elongate member on a surface of one of the two rotary members. Also, in one or more of the embodiments described herein, the method may include removing the elongate member from the first and second rotary members while maintaining the elongate member in a patient's anatomy.

Other methods for manipulating an elongate member are also provided. For example, in accordance with other embodiments, a method of manipulating an elongate member in two degrees of freedom includes transferring rotational motion across a sterile barrier to generate a corresponding linear motion of the elongate member along a longitudinal axis of the elongate member, and transferring linear motion across the sterile barrier to generate a corresponding rotational motion of the elongate member about the longitudinal axis of the elongate member. In some embodiments, the rotational motion and the linear motion may be transferred simultaneously. Also, in some embodiments, the rotational motion and linear motion may be transferred at different respective rates. In one or more of the embodiments described herein, the rotational motion and the linear motion may be transferred separately, and wherein between the acts of transferring, the elongate member may be maintained in engagement with rotary members.

In accordance with other embodiments, a method of manipulating an elongate member in two degrees of freedom includes engaging a first continuous surface with the elongate member, engaging a second continuous surface with the elongate member, actuating the first surface and second surface in opposite linear directions to generate a rotational motion of the elongate member about the longitudinal axis of the elongate member, and actuating the first surface and second surface in opposite rotational directions to generate a linear motion of the elongate member along the longitudinal axis of the elongate member. In some embodiments, the rotational motion and the linear motion may be generated simultaneously. Also, in some embodiments, the rotational motion and the linear motion may be generated at different respective rates. In one or more of the embodiments described herein, the rotational motion and the linear motion may be generated separately, and wherein the first and second continuous surfaces maintain engagement with the elongate member between the generation of the rotational motion and the linear motion.

The robotic system may also optionally include a user interface for allowing a user to operate the robotic system in accordance with some embodiments. The user interface may provide a variety of features. By means of non-limiting examples, the user interface may allow a user to align a representation of a catheter with an image of the catheter in a screen in some embodiments. In other embodiments, the user interface may provide a graphic for informing a user a constraint that is imposed by the system on manipulating the elongate instrument.

In some embodiments, the user interface may be implemented using a processor. For example, in accordance with some embodiments, a system includes a processor configured for generating a virtual representation of a catheter on a viewing screen, a first control for allowing a user to rotate the virtual representation of the catheter about a first axis, until a heading direction of the virtual representation of the catheter aligns with a heading direction of the catheter as it appears in a first fluoroscopic image, and a second control for allowing the user to rotate the virtual representation of the catheter about a second axis, until a tilt angle of the virtual representation of the catheter aligns with a tilt angle of the catheter as it appears in the first fluoroscopic image or in a second fluoroscopic image. In some embodiments, the first control may include a first slider in a touchscreen. Also, in some embodiments, the second control may include a second slider in the touchscreen. In other embodiments, the first control may include a trackball. In one or more of the embodiments described herein, the first control may be configured for rotating the virtual representation of the catheter about the first axis in a plane of the screen. In some embodiments, the system may also include an actuator coupled to the catheter and configured for bending the catheter, and a third control coupled to the actuator for allowing the user to move the bent catheter into alignment with a roll of the virtual representation of the catheter. In one or more of the embodiments described herein, the system may include a third control for allowing the user to move the virtual representation of the catheter into alignment with a roll of the catheter. Also, in one or more of the embodiments described herein, the catheter may have a bent configuration.

In some embodiments, the processor may be configured for generating the virtual representation of the catheter using kinematic information regarding the catheter. In one or more of the embodiments described herein, the processor may be configured for generating the virtual representation of the catheter based at least in part on a signal transmitted through a fiber optic that extends along a length of the catheter. In one or more of the embodiments described herein, the processor may be configured for generating the virtual representation of the catheter based at least in part on localization data obtained from electromagnetic sensors.

In some embodiments, a method may be implemented using a user interface that allows a user to align a representation of an elongate device with an image of an elongate device. For example, in accordance with some embodiments, a method includes generating a virtual representation of the catheter on a viewing screen, providing a first control for allowing a user to rotate the virtual representation of the catheter about a first axis, until a heading direction of the virtual representation of the catheter aligns with a heading direction of the catheter as it appears in a first fluoroscopic image, and providing a second control for allowing the user to rotate the virtual representation of the catheter about a second axis, until a tilt angle of the virtual representation of the catheter aligns with a tilt angle of the catheter as it appears in the first fluoroscopic image or in a second fluoroscopic image. In some embodiments, the first control may include a first slider in a touchscreen. Also, in some embodiments, the second control may include a second slider in the touchscreen. In other embodiments, the first control may include a trackball. In some embodiments, the virtual representation may be generated using kinematic information regarding the catheter. In other embodiments, the virtual representation may be generated based at least in part on a signal transmitted through a fiber optic that extends along a length of the catheter. In one or more of the embodiments described herein, the first control may be provided for rotating the virtual representation of the catheter about the first axis in a plane of the screen. Also, in one or more of the embodiments described herein, the method may include providing a third control coupled to an actuator configured for moving the catheter for allowing the user to move the catheter until the appearance of the catheter in the first or second fluoroscopic image is in alignment with a roll of the virtual representation of the catheter. In other embodiments, the method may include providing a third control for allowing the user to move the virtual representation of the catheter into alignment with a roll of the catheter as it appears in the first or second fluoroscopic image. In one or more of the embodiments described herein, the catheter may have a bent configuration.

In accordance with other embodiments, a computer product includes a non-transitory medium storing a set of instructions, an execution of which causes a method for registering an image of a catheter with a virtual representation of the catheter to be performed, the set of instructions comprising one or more instructions for generating a virtual representation of the catheter on a viewing screen, one or more instructions for allowing a user to manipulate a first control to rotate the virtual representation of the catheter about a first axis, until a heading direction of the virtual representation of the catheter aligns with a heading direction of the catheter as it appears in a first fluoroscopic image, and one or more instructions for allowing the user to manipulate a second control to rotate the virtual representation of the catheter about a second axis, until a tilt angle of the virtual representation of the catheter aligns with a tilt angle of the catheter as it appears in the first fluoroscopic image or in a second fluoroscopic image. In some embodiments, the first control may include a first slider in a touchscreen. Also, in some embodiments, the second control may include a second slider in the touchscreen. In other embodiments, the first control may include a trackball. In one or more of the embodiments described herein, manipulation of the first control may allow the user to rotate the virtual representation of the catheter about the first axis in a plane of the screen. Also, in one or more of the embodiments described herein, the set of instructions may further include one or more instructions for allowing the user to manipulate a third control for moving the catheter, until the catheter as it appears in the first or second fluoroscopic image is in alignment with a roll of the virtual representation of the catheter. In one or more of the embodiments described herein, the set of instructions may further include one or more instructions for allowing the user to manipulate a third control for moving the virtual representation of the catheter into alignment with a roll of the catheter as it appears in the first or second fluoroscopic image. In some embodiments, the one or more instructions for generating the virtual representation may include one or more instructions for using kinematic information regarding the catheter to generate the virtual representation. In other embodiments, the one or more instructions for generating the virtual representation may include one or more instructions for generating the virtual representation based at least in part on a signal transmitted through a fiber optic that extends along a length of the catheter. In one or more of the embodiments described herein, the catheter may have a bent configuration.

In accordance with other embodiments, a user interface for controlling a robotic system includes a screen displaying an image of a catheter and a dome at a distal end of the catheter, wherein the dome represents a constraint for the distal end of the catheter so that at least a part of the distal end of the catheter is required to be on an outline of the dome regardless of how the catheter is driven. By means of non-limiting examples, the dome may have a cardiod shape, a spherical shape, or any shape that is user defined/computer calculated. In some embodiments, the user interface may include a first control for allowing the user to advance or retrace the catheter, and a second control for allowing the user to steer the catheter. Also, in some embodiments, advancement or retraction of the catheter may change a size of the dome in the screen. In further embodiments, a steering of the catheter may not change a size of the dome in the screen. In one or more of the embodiments described herein, the user interface may include a user control configured to provide force feedback to a user. Also, in one or more of the embodiments described herein, the user control may be configured to provide force feedback when the user attempts to position the at least a part of the distal end of the catheter away from the outline of the dome. In some embodiments, the image of the catheter may include a computer model of the catheter.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings illustrate the design and utility of embodiments, in which similar elements are referred to by common reference numerals. These drawings are not necessarily drawn to scale. In order to better appreciate how the above-recited and other advantages and objects are obtained, a more particular description of the embodiments will be rendered, which are illustrated in the accompanying drawings. These drawings depict only typical embodiments and are not therefore to be considered limiting of its scope.

FIG. **1** illustrates a robotic surgical system in which apparatus, system and method embodiments may be implemented.

FIG. **2** illustrates an example of an operator workstation of the robotic surgical system shown in FIG. **1** with which a catheter instrument can be manipulated using different user interfaces and controls.

FIG. **3**A illustrates a support assembly or mounting brace for a instrument driver of a robotic surgical system.

FIG. **3**B further illustrates the support assembly illustrated in FIG. **3**A.

FIG. **3**C is another view of the support assembly shown in FIGS. **3**A-B with an attached instrument driver.

FIG. **3**D is a perspective view of a support arm adapter base plate assembly configured for attaching a support assembly to an operating table or surgical bed.

FIG. **3**E further illustrates how the adapter base plate assembly is utilized to attach a support assembly and instrument driver to an operating table or surgical bed.

FIG. **4** illustrates an instrument driver mounted to a distal segment of a support assembly.

FIG. **5**A illustrates a sheath and guide catheter assembly mounted on an instrument driver.

FIG. **5**B further illustrates the instrument driver shown in FIG. **5**A without the sheath and guide catheter assembly.

FIG. **5**C further illustrates the instrument driver shown in FIG. **5**B with skins removed and one of the mounting plates being moved relative to the mounting plate arrangement shown in FIG. **5**B.

FIG. **6**A illustrates a sheath and guide catheter assembly positioned over respective mounting plates.

FIG. **6**B further illustrates how sheath and guide splayers interface with respective mounting plates.

FIG. **7** illustrates an exploded view of the sheath splayer shown in FIG. **6**B without a purge tube.

FIG. **7**A illustrates a pulley assembly of the splayer shown in FIG. **7**.

FIG. **7**B illustrates an exploded view of the pulley assembly shown in FIG. **7**A.

FIG. **7**C illustrates the top portion of the pulley assembly shown in FIG. **7**A.

FIG. **7**D illustrates the bottom portion of the pulley assembly shown in FIG. **7**A.

FIG. **7**E illustrates a bottom perspective view of a cover of the splayer shown in FIG. **7**.

FIG. **7**F illustrates an exploded view of a splayer base assembly of the splayer shown in FIG. **7**.

FIG. **8**A illustrates a guide carriage of the instrument driver shown in FIG. **5**C coupled to cabling and guide motors.

FIG. **8**B is a perspective view of a slidable carriage or funicular assembly of an instrument driver and receiver slots configured to receive and engage with splayer shafts.

FIG. **9**A is a perspective view of a drive shaft positioned for insertion into a sleeve receptacle located on an instrument driver.

FIG. **9**B of a drive shaft that is inserted into a sleeve receptacle.

FIG. **10** illustrates a sheath block and guide insert motor and leadscrew removed from the instrument driver shown in FIG. **5**C.

FIGS. **10**A and **10**B illustrate different perspective views of the sheath block.

FIGS. **11**A-**11**H illustrate side and cross-sectional views of a catheter bent in various configurations with pull wire manipulation.

FIG. **12** shows an example of an overview block diagram of a basic topology for controlling flexible devices.

FIG. **13** illustrates forward kinematics and inverse kinematics in accordance with some embodiments.

FIG. **14** illustrates task coordinates, joint coordinates, and actuation coordinates in accordance with some embodiments.

FIG. **15** illustrates variables associated with a geometry of a catheter in accordance with some embodiments.

FIG. **16** illustrates a conventional open loop control model.

FIG. **17** illustrates a control system in accordance with some embodiments.

FIG. **18** illustrates a user interface for a master input device.

FIGS. **19-29** illustrate software control schema in accordance with various embodiments.

FIG. **30** illustrates a distal portion of a guide catheter extending beyond a distal end of a sheath instrument by a distance or length L_1 and a force F imparted on the distal tip of the guide catheter that may cause the distal portion of the guide catheter to bend or flex.

FIG. **31** illustrates a distal portion of a guide catheter extending beyond a distal end of a sheath instrument by a distance or length L_2 that is less than the length L_1 shown in FIG. **30**.

FIG. **32** illustrates assessing reachability and viewability or field of view according to one embodiment.

FIG. **33**A illustrates a cross-sectional view of a flexible and steerable elongate instrument with variable or changeable shape control and support elements in accordance with one embodiment.

FIG. **33**B illustrates another cross-sectional view (View **1-1**) of a flexible and steerable elongate instrument with variable or changeable shape control and support elements in accordance with one embodiment.

FIG. **34**A illustrates an elongate instrument with passively controlled flex member in accordance with one embodiment.

FIG. **34**B illustrates a passively controlled flex member with a service or buffer loop in accordance with one embodiment.

FIG. **34**C illustrates support tubes or support members sliding along the flex tubes or flex members in accordance with one embodiment.

FIG. **34**D illustrates slidable couplings of variable shape control and support components near the proximal section of a flexible and steerable elongate instrument in accordance with one embodiment.

FIGS. **35**A-**35**C illustrate the operation of a substantially flexible and steerable elongate instrument in accordance with one embodiment.

FIG. **36**A and FIG. **36**B illustrate curve aligned steering of a flexible and steerable elongate instrument in accordance with one embodiment.

FIG. **36**C illustrates an embodiment of an elongate instrument that does not have coil pipes.

FIG. **36**D illustrates a mechanics of a coil pipe in accordance with some embodiments.

FIGS. **37**A-**37**E illustrate another catheter in accordance with other embodiments.

FIGS. **38-44** illustrate a sheath in accordance with some embodiments, and variations thereof.

FIGS. **45-48** illustrate methods of using a catheter and a sheath in accordance with different embodiments.

FIGS. **49-50**C illustrate a valve in accordance with some embodiments.

FIGS. **51**A-**51**F illustrate another robotic surgical system **400** in accordance with other embodiments.

FIG. **51**G illustrates a rail system configured to tilt a setup mount in accordance with some embodiments.

FIG. **52**A illustrates driving mode(s) in accordance with some embodiments.

FIG. **52**B illustrates driving mode(s) in accordance with other embodiments.

FIG. **52**C illustrates driving mode(s) in accordance with other embodiments.

FIG. **52**D illustrates driving mode(s) in accordance with other embodiments.

FIGS. **53**A-**67**C illustrate different anti-buckling devices, and components that operate with the anti-buckling devices, in accordance with different embodiments; and

FIGS. **68-78**A illustrate different lubricating mechanisms in accordance with different embodiments.

FIG. **79**A illustrates a front perspective view of a variation of an elongate member manipulator.

FIG. **79**B illustrates an end perspective view of the elongate member manipulator of FIG. **79**A.

FIG. **79**C illustrates a cross sectional view of the elongate member manipulator of FIG. **79**A.

FIG. **79**D illustrates a top cross sectional view of the elongate member manipulator of FIG. **79**A.

FIGS. **80**A-**80**B are schematic illustrations showing top and front views of feed rollers actuating an elongate member.

FIG. **81** illustrates a cross sectional view of one variation of a roller actuator.

FIG. **82** illustrates a cross sectional view of one variation of a feed roller with a drape,

FIG. **83** illustrates a perspective view of the instrument driver, the guide splayer and a variation of an elongate member manipulator.

FIG. **83**A illustrates a closer view of the instrument driver, the elongate member manipulator, and the guide splayer of FIG. **83**.

FIG. **84** illustrates a perspective view of the elongate member manipulator of FIG. **83**, showing the manipulator in an open configuration and mounted to a manipulator mounting bracket.

FIG. **85**A illustrates the elongate member manipulator of FIG. **84**, showing the manipulator in a closed configuration.

FIGS. **85**B-**85**C illustrate the elongate member manipulator of FIG. **84** with an idler belt assembly removed, showing the manipulator open by varying degrees.

FIG. **85**D illustrates the elongate member manipulator of FIG. **85**B in a closed configuration.

FIG. **85**E illustrates a cross-sectional view of the elongate member manipulator of FIG. **85**A.

FIG. **86**A illustrates a back view of the elongate member manipulator of FIG. **84**.

FIGS. **86**B-**86**C illustrates various perspective views of the elongate member manipulator of FIG. **85**.

FIG. **87**A illustrates a side view of the elongate member manipulator of FIG. **85**, showing a hinge mechanism in a closed configuration.

FIG. **87**B illustrates the elongate member manipulator of FIG. **87**A, showing the hinge mechanism in an open configuration.

FIG. **87**C illustrates a cross sectional perspective view of the elongate member manipulator of FIG. **84**.

FIG. **88** illustrates a perspective view of the elongate member manipulator of FIG. **84** with wire holders installed, showing both the manipulator and wire holders in open configurations.

FIG. **89** illustrates the elongate member manipulator of FIG. **88**, showing the manipulator and wire holders in closed configurations.

FIG. **90**A illustrates an exploded perspective view of the elongate member manipulator of FIG. **84**, showing the idler belt assembly and a drive belt assembly partially removed.

FIG. **90**B illustrates a cross sectional view of the elongate member manipulator of FIG. **84**, showing the idler belt assembly and the drive belt assembly partially un-installed.

FIG. **90**C illustrates a cross sectional view of the elongate member manipulator of FIG. **84**, showing the idler belt assembly and the drive belt assembly fully installed.

FIGS. **91**A-**91**C illustrate perspective views of the instrument driver, the guide splayer and another alternative variation of an elongate member manipulator.

FIGS. **91**D-**91**E illustrate perspective views of the elongate member manipulator of FIG. **91**A.

FIG. **91**F illustrates a perspective view of the elongate member manipulator of FIG. **91**A, showing the elongate member manipulator in an open configuration.

FIG. **91**G illustrates a side view of the elongate member manipulator of FIG. **91**A, showing the manipulator mounting bracket, a roll motor, and an insert motor all removed.

FIG. **91**H illustrates a cross sectional side view of the elongate member FIG. **91**A, showing the manipulator mounting bracket, the roll motor, and the insert motor all removed.

FIGS. **92**A-**92**B illustrate perspective views of an idler belt assembly of the elongate member manipulator of FIG. **91**A.

FIGS. **93**A-**93**D illustrate various perspective views of a drive belt assembly of the elongate member manipulator of FIG. **91**A.

FIG. **94**A illustrates a perspective view of an elongate member support of the elongate member manipulator of FIG. **91**A.

FIG. **94**B illustrates a cross sectional top view of the elongate member support of FIG. **94**A.

FIG. **94**C illustrates an alternative perspective view of the elongate member manipulator of FIG. **91**A, showing the manipulator mounted to a manipulator mounting bracket.

FIG. **94**D illustrates the elongate member manipulator of FIG. **94**C, showing an insert motor cover removed.

FIG. **94**E illustrates a zoomed in view of the insert motor of the elongate member manipulator of FIG. **94**D.

FIG. **95**A illustrates a perspective view of a valve holder of the elongate member manipulator of FIG. **91**A, showing the valve holder in a closed configuration.

FIGS. **95**B-**95**C illustrate various perspective views of the valve holder of FIG. **95**A in an open configuration.

FIGS. **95**D-**95**E illustrate front and back perspective views of a valve assembly of the elongate member manipulator of FIG. **91**A, showing a support tube and guide wire installed.

FIG. **95**F illustrates an exploded perspective view of the valve assembly of FIG. **95**D, showing the support tube and guide wire removed.

FIG. **96** illustrates the drive belt assembly and idler belt assembly of FIG. **91**A, showing a portion of the drape.

FIG. **96**A illustrates a cross sectional bottom view of the drive belt assembly of FIG. **94**A.

FIG. **96**B illustrates a cross sectional bottom view of the idler belt assembly of FIG. **92**A.

FIG. **96**C illustrates a perspective view of a representation of an alternative elongate member manipulator with a guide wire installed.

FIG. **96**D-**96**E illustrate side views of the elongate member manipulator of FIG. **96**C showing roll actuation of the guide wire.

FIG. **97** illustrates a perspective view of another variation of an elongate member manipulator mounted to a variation of an instrument driver.

FIGS. **97***aa*-**97***ab* illustrate various views of the elongate member manipulator of FIG. **97** with a cover removed.

FIGS. **97**A**1**-**97**A**2** illustrate a front view of the elongate member manipulator of FIG. **97** in an closed and open configuration respectively.

FIGS. **97**A**3**-**97**A**4** illustrate a back view of the elongate member manipulator of FIG. **97** in an closed and open configuration respectively.

FIGS. **97**B**1**-**97**B**2** illustrate front and back perspective views of the elongate member manipulator of FIG. **97**A**1** with the cover removed.

FIG. **97**B**3** illustrates a zoomed in view of a roll motor and accompanying roll mechanisms.

FIG. **97**C illustrates the elongate member manipulator of FIGS. **97**B**1**-**97**B**2** with only insert mechanical components and a drive belt assembly displayed.

FIG. **97**D**1** illustrates a perspective view of the drive belt assembly of FIG. **97**C.

FIG. **97**D**2** illustrates a cross sectional view of the drive belt assembly of FIG. **97**D**1**.

FIG. **97**D**3** illustrates a zoomed in view of a drive shaft shown in FIG. **97**D**2**.

FIGS. **97**E**1**-E**2** illustrate upper and lower slide assemblies of the elongate member manipulator of FIG. **97**C with the drive belt assembly and an idler belt assembly installed and un-installed respectively.

FIG. **97**F illustrates an exploded view of the upper slide assembly of FIGS. **97**E**1**-**97**E**2**.

FIG. **97**G illustrates a top, front and side view of a simplified representation of an alignment bar and cradle of the upper slide assembly shown in FIG. **97**F.

FIG. **97**H**1** illustrates the elongate member manipulator of FIG. **97**A**1** with the drive and idler belt assemblies removed.

FIG. **97**H**2** illustrates a view of the elongate member manipulator of FIG. **97**H**1** with an elongate member holder exploded from the elongate member manipulator.

FIG. **97**J**1** illustrates the elongate member holder of FIGS. **97**H**1**-**97**H**2** with a guide wire and valve installed.

FIG. **97**J**2** illustrates the elongate member holder of FIG. **97**J**1** with a valve holder in an open configuration and the guide wire and valve exploded from the elongate member holder.

FIGS. **97**J**3**-**97**J**4** illustrate different perspective views of the valve holder of FIGS. **97**J**1**-**97**J**2** in closed and open configurations respectively.

FIGS. **97**K**1** and K**2** illustrate perspective views of a drape assembly.

FIGS. **97**L**1**-**97**L**2** illustrate top and bottom perspective views of a tenting frame of the drape assembly shown in FIGS. **97**K**1**-**97**K**2**.

FIGS. **97**M**1**-**97**M**5** illustrate the drape assembly of FIG. **97**K being installed on a simplified model of the elongate member manipulator of FIG. **97**A**1**.

FIGS. **97**M**6**-**97**M**7** illustrate the drape installed on the elongate member manipulator of FIG. **97**A**1** in a closed and open configuration respectively.

FIG. **98**A illustrates a perspective view of an instrument driver with a guide splayer and another variation of an elongate member manipulator.

FIG. **98**B illustrates a closer view of the instrument driver, guide splayer, and elongate member manipulator of FIG. **98**A.

FIG. **99** illustrates a perspective view of the elongate member manipulator of FIG. **98**A.

FIGS. **100**A-**100**B illustrate perspective views of the elongate member manipulator of FIG. **99**, showing a motor pack cover removed.

FIGS. **101**A-**101**B illustrate front and back perspective views of a belt assembly of the elongate member manipulator of FIG. **99**.

FIG. **101**C illustrates a back view of the belt assembly of FIG. **101**A.

FIG. **102**A illustrates a side view of the belt assembly of FIG. **101**A.

FIG. **102**B illustrates the belt assembly of FIG. **102**A, shown in an open configuration.

FIG. **103** illustrates a perspective view of the instrument driver, guide splayer, and an alternative variation of an elongate member manipulator, showing the manipulator un-installed.

FIGS. **103**AA-**103**AB illustrate perspective and side views of an adapted Tiny-Vise clamp.

FIG. **103**A illustrates a top view of the elongate member manipulator of FIG. **103**, showing a guide wire and a roll support tube.

FIG. **103**B illustrates a top view of the elongate member manipulator of FIG. **103**, showing a guide wire and a scissor jack support.

FIG. **104** illustrates a perspective view of the elongate member manipulator of FIG. **103**, showing a motor pack cover removed.

FIG. **105** illustrates a perspective view of a feed roller assembly of the elongate member manipulator of FIG. **104**.

FIG. **106**A illustrates a closer view of the feed roller assembly of FIG. **105**.

FIGS. **106**B-**107**A illustrate a top view of the feed roller assembly of FIG. **105**.

FIG. **107**B illustrates a bottom view of the feed roller assembly of FIG. **105**.

FIG. **108**A illustrates a representation of the bottom view of a gear train of the feed roller assembly of FIG. **105**.

FIG. **108**B illustrates the gear train representation of FIG. **108**A, showing the gear train pivoted in an open configuration.

FIG. **109** illustrates a side view of a drive roller and feed roller of FIG. **105**, showing a guide wire installed.

FIG. **110**A illustrates a top view of the feed roller assembly of FIG. **105**, showing an insert assembly removed from an actuation assembly.

FIG. **110**B illustrates a perspective view of the feed roller assembly.

FIGS. **111**A-**111**F illustrate top views of simplified representations of various feed roller and feed belt combinations.

FIG. **112**A illustrates a bottom perspective view of the elongate member manipulator of FIG. **85**.

FIG. **112**B illustrates a bottom perspective view of the elongate member manipulator of FIG. **104**.

FIG. **113** illustrates a top view of a variation of a control console of the operator workstation of FIG. **1**.

FIG. **114**A illustrates a perspective view of a patient bed of the robotic instrument system of FIG. **1**, showing a standalone console mounted to the patient bed.

FIG. **114**B illustrates a side view of the standalone console of FIG. **114**A, showing the standalone console mounted to a mounting bracket and a bed rail.

FIG. **115** illustrates a top view of a variation of the standalone console of FIG. **114**A.

FIGS. **116** and **117**A-**117**M illustrate variations of a master input device.

FIGS. **118**A-D illustrate flow diagrams of various master-slave control options.

FIG. **119** illustrates a perspective view of the instrument driver and the elongate member manipulator of FIG. **91**A with an anti-buckling mechanism installed.

FIG. **120** illustrates a flow diagram of a variation of a control scheme for control of the elongate member manipulator of FIG. **79**A, **85**, **91**A, **99**, **103**A, or **124**A.

FIGS. **121**A-**121**B illustrate block diagrams representing the instrument driver, the elongate member manipulator, the guide catheter, and the sheath catheter.

FIG. **122** illustrates a flow diagram of the controller for the configuration with a movable carriage and a coupled elongate member manipulator of FIG. **121**B.

FIG. **123** illustrates a representation of a variation of a virtual guide wire.

FIG. **124**A illustrates a perspective view of another alternative variation of an elongate member manipulator.

FIGS. **124**B-C illustrates perspective views of the elongate member manipulator of FIG. **124**A, showing the manipulator cover removed.

FIGS. **125**A and **127**A illustrate a perspective views of a rotation drive of the elongate member manipulator of FIG. **124**C.

FIG. **125**B illustrates a side perspective view of the rotation drive of FIG. **125**A with the guide wire installed.

FIG. **125**C illustrates a closer perspective view of the rotation drive of FIG. **125**A.

FIG. **126** illustrates a side cross sectional view of the elongate member manipulator of FIG. **124**B.

FIG. **127**B illustrates a side cross sectional view of the rotation drive of FIG. **125**A.

FIG. **127**C illustrates a side and a cross sectional view of the rotation drive of FIG. **125**A.

FIG. **128**A illustrates a control system in accordance with some embodiments.

FIG. **128**B illustrates a localization sensing system having an electromagnetic field receiver in accordance with some embodiments.

FIG. **128**C illustrates a localization sensing system in accordance with other embodiments.

FIG. **128**D illustrates a user interface for a master input device in accordance with some embodiments.

FIG. **128**E illustrates a configuration of a catheter in accordance with some embodiments.

FIG. **128**F illustrates another configuration of a catheter in accordance with other embodiments.

FIG. **128**G illustrates a catheter that is haptically constrained to a surface of a "dome" in accordance with some embodiments.

FIG. **129***a* is a perspective view of an instrument driver with a sheath and guide splayer installed.

FIG. **129***b* is a zoomed in view of the sheath splayer mounted to the instrument driver of FIG. **129***a*.

FIG. **129***c* is an exploded view of the sheath splayer and instrument driver of FIG. **129***b*.

FIGS. **130***a* and **130***b* are top and bottom perspective view respectively of a sheath output plate.

FIG. **130***c* is an exploded bottom perspective view of the sheath output plate of FIG. **130***a*.

FIGS. **131***a* and **131***b* are top and bottom perspective views respectively of a base plate.

FIG. **131***c* is a perspective view of a guide output plate.

FIGS. **132***a* and **132***b* are top and bottom perspective views respectively of a drive interface apparatus.

FIG. **132***c* is an exploded perspective view of the drive interface apparatus of FIG. **132***a*.

FIGS. **133***a* and **133***b* are top perspective views respectively of a drive interface base.

FIGS. **134***a* and **134***b* are top and bottom perspective view respectively of the drive interface base of FIG. **133***a* populated with a plurality of drive interface pulley shafts and a pair of EEPROM pins.

FIG. **135***a* is a perspective view of a drape assembly.

FIG. **135***b* is a zoomed in perspective view of a portion of the drape assembly of FIG. **135***a* including a sheath foam pad.

FIG. **135***c* is a zoomed in perspective view of a portion of the drape assembly of FIG. **135***a* including a guide foam pad.

FIG. **136***a* is a perspective view of a sheath splayer.

FIG. **136***b* is a perspective view of a guide splayer.

FIG. **136***c* is a perspective view of the sheath splayer of FIG. **136***a* with a splayer cover exploded from the sheath splayer.

FIGS. **137***a* and **137***b* are top and bottom perspective views respectively of a splayer body.

FIG. **137***c* is an exploded perspective view of the splayer body of FIG. **137***a*.

FIG. **138** is a bottom view of a splayer cover.

FIGS. **138***a* and **138***b* are perspective and exploded views respectively of a splayer pulley assembly.

FIGS. **139***a* and **139***b* are top and bottom perspective views respectively of a splayer base.

FIGS. **140***a* and **140***b* are top and bottom perspective views respectively of the splayer base of FIG. **139***a* populated with a plurality of splayer pulley assemblies, a splayer presence magnet, and a splayer ID chip.

FIGS. **141***a* and **141***b* illustrate methods of installing the drape assembly of FIG. **135***a* over the instrument driver.

FIG. **142***a* is a perspective view of the instrument assembly with the drape assembly installed and the drive interface apparatus exploded from the instrument driver.

FIG. **142***b* is a perspective view of the instrument assembly and drape assembly of FIG. **142***a* with the drive interface apparatus installed.

FIG. **143***a* is a top perspective view of the sheath output plate with the drape assembly installed and the drive interface apparatus exploded.

FIG. **143***b* is a bottom perspective view of the sheath output plate, drape assembly, and drive interface apparatus of FIG. **143***a*.

FIG. **143***c* is a bottom perspective view of the sheath output plate with the drape and drive interface apparatus installed.

FIGS. **144***a* and **144***b* are perspective views of a drive interface pulley shaft installed and uninstalled respectively to a sleeve receptacle.

FIGS. **144***c* and **144***d* are side and front views of the drive interface pulley and sleeve receptacle illustrated in FIG. **144***b*.

FIGS. **145***a* and **145***b* are top and bottom perspective view of the sheath splayer exploded from the drive interface apparatus.

FIG. **146***a* is a top view of the splayer pulley assembly.

FIG. **146***b* is a top view of the drive interface pulley shaft.

FIGS. **147***a* and **147***b* are top and bottom perspective views respectively of the splayer pulley assembly exploded from the drive interface pulley shaft.

FIGS. **148***a* and **148***b* are top and bottom exploded views respectively of the instrument driver with the drape assembly installed and the drive interface apparatus and sheath splayer un-installed.

DESCRIPTION OF THE EMBODIMENTS

Various embodiments are described hereinafter with reference to the figures. It should be noted that the figures are not drawn to scale and that elements of similar structures or functions are represented by like reference numerals throughout the figures. It should also be noted that the figures are only intended to facilitate the description of the embodiments. They are not intended as an exhaustive description of the invention or as a limitation on the scope of the invention. In addition, an illustrated embodiment needs not have all the aspects or advantages shown. An aspect or an advantage described in conjunction with a particular embodiment is not necessarily limited to that embodiment and can be practiced in any other embodiments even if not so illustrated.

I. Robotic Surgical Systems

Embodiments described herein generally relate to apparatus, systems and methods for robotic surgical systems. A robotic surgical systems in which embodiments described herein may be implemented is described with reference to FIGS. **1**-**10**B. Various embodiments of apparatus, system and method, including control and electronic architectures, are described with reference to FIGS. **11**A-**19**K. Various embodiments directed to indicating catheter insertion forces as the catheter engages tissue or another object are described with reference to FIGS. **20**A-B. Various embodiments directed to determining reachability of catheter instrument and viewability or fields of view at different reachable locations are described with reference to FIG. **21**.

Referring to FIG. **1**, a robotically controlled surgical system (S) in which embodiments of apparatus, system and method may be implemented includes a robotic catheter assembly (A) having a first or outer robotic steerable complement, otherwise referred to as a sheath instrument **30** (generally referred to as “sheath” or “sheath instrument”) and/or a second or inner steerable component, otherwise referred to as a robotic catheter or guide or catheter instrument **18** (generally referred to as “catheter” or “catheter instrument”). The sheath instrument **30** and catheter instrument **18** are controllable using a robotic instrument driver **16** (generally referred to as “instrument driver”). During use, a patient is positioned on an operating table or surgical bed **22** (generally referred to as “operating table”) to which a robotic catheter assembly (A) is coupled or mounted. In the illustrated example, the system (S) includes an operator workstation **2**, an electronics rack **6** and associated bedside electronics box, a setup joint mounting brace **20**, and an instrument driver **16**. A surgeon is seated at the operator workstation **2** and can monitor the surgical procedure, patient vitals, and control one or more catheter devices.

Various system (S) components in which embodiments described herein may be implemented are illustrated in close proximity to each other in FIG. **1**, but embodiments may also be implemented in systems (S) in which components are separated from each other, e.g., located in separate rooms. For example, the instrument driver **16**, operating table **22**, and bedside electronics box may be located in the surgical area with the patient, and the operator workstation **2** and the electronics rack **6** may be located outside of the surgical area and behind a shielded partition. System (S) components may also communicate with other system (S) components via a network to allow for remote surgical procedures during which the surgeon may be located at a different location, e.g., in a different building or at a different hospital utilizing a communication link transfers signals between the operator control station **2** and the instrument driver **16**. System (S) components may also be coupled together via a plurality of cables or other suitable connectors **14** to provide for data communication, or one or more components may be equipped with wireless communication components to reduce or eliminate cables **14**. In this manner, a surgeon or other operator may control a surgical instrument while being located away from or remotely from radiation sources, thereby decreasing the operator’s exposure to radiation.

Referring to FIG. **2**, one example of an operator workstation **2** that may be used with the system (S) shown in FIG. **1** includes three display screens **4**, a touch screen user interface **5**, a control button console or pendant **8**, and a master input device (MID) **12**. The MID **12** and pendant **8** serve as user interfaces through which the surgeon can control operation of the instrument driver **16** and attached instruments. By manipulating the pendant **8** and the MID **12**, a surgeon or other operator can cause the instrument driver **16** to remotely control a catheter instrument **18** and/or a sheath instrument **30** mounted thereon. A switch **7** may be provided to disable activity of an instrument temporarily. The console **2** in the illustrated system (S) may also be configurable to meet individual user preferences. For example, in the illustrated example, the pendant **8** and the touch screen **5** are shown on the left side of the console **2**, but they may also be relocated to the right side of the console **2**. Further, optional keyboard may be connected to the console **2** for inputting user data. The workstation **2** may also be mounted on a set of casters or wheels to allow easy movement of the workstation **2** from one location to another, e.g., within the operating room or catheter laboratory. Further aspects of examples of suitable MID **12**, and workstation **2** arrangements are described in further detail in U.S. patent application Ser. No. 11/481,433 and U.S. Provisional Patent Application No. 60/840,331, the contents of which were previously incorporated herein by reference. Additional embodiments of various MIDs and pendants will also be described later.

Referring to FIGS. **3**A-C, a system (S) includes a setup joint or support assembly **20** (generally referred to as “support assembly”) for supporting or carrying the instrument driver **16** over the operating table **22**. One suitable support assembly **20** has an arcuate shape and is configured to position the instrument driver **16** above a patient lying on the table **22**. The support assembly **20** may be configured to movably support the instrument driver **16** and to allow convenient access to a desired location relative to the patient. The support assembly **20** may also be configured to lock the instrument driver **16** into a certain position.

In the illustrated example, the support assembly **20** is mounted to an edge of the operating table **22** such that a catheter and sheath instruments **18**, **30** mounted on the instrument driver **16** can be positioned for insertion into a patient. The instrument driver **16** is controllable to maneuver the catheter and/or sheath instruments **18**, **30** within the patient during a surgical procedure. The distal portion of the setup joint **20** also includes a control lever **33** for maneuvering the setup joint **20**. Although the figures illustrate a single guide catheter **18** and sheath assembly **30** mounted on a single instrument driver **16**, embodiments may be implemented in systems (S) having other configurations. For example, embodiments may be implemented in systems (S) that include a plurality of instrument drivers **16** on which a plurality of catheter/sheath instruments **18**, **30** can be controlled. Further aspects of a suitable support assembly **20** are described in U.S. patent application Ser. No. 11/481,433 and U.S. Provisional Patent Application No. 60/879,911, the contents of which are expressly incorporated herein by reference. Referring to FIG. **3**D-E, the support assembly **20** may be mounted to an operating table **22** using a universal adapter base plate assembly **39**, similar to those described in detail in U.S. Provisional Patent Application No. 60/899,048, incorporated by reference herein in its entirety. The adapter plate assembly **39** mounts directly to the operating table **22** using clamp assemblies **39***b*, **39***c*, and the support assembly **20** can be mounted to the adapter plate assembly **39**. One suitable adapter plate assembly **39** includes a large, flat main plate **39***a* which is positioned on top of the operating table **22**. The assembly **39** provides for various adjustments to allow it to be mounted to different types of operating tables **22**. An edge of the adapter plate assembly **39** may include a rail **39***d* that mimics the construction of a traditional surgical bedrail. By placing this rail on the adapter plate **39***a* itself, a user may be assured that the component dimensions provide for proper mounting of the support assembly **20**. Furthermore, the large, flat surface of the main plate **39***a* provides stability by distributing the weight of the support assembly **20** and instrument driver **16** over an area of the table **22**, whereas a support assembly **20** mounted directly to the operating table **22** rail may cause its entire load to be placed on a limited and less supportive section of the table **22**.

With further reference to FIGS. **4** and **5**A, an instrument assembly (A) comprised of a sheath instrument **30** and an associated guide or catheter instrument **18** is mounted to associated mounting plates **37**, **38** on a top portion of the instrument driver **16**. FIG. **5**B illustrates the instrument driver **16** without an attached instrument assembly (A). FIG. **5**C illustrates the instrument driver **16** with skins removed to illustrate internal components which will be described in further detail. Embodiments described are similar to those described in detail in U.S. patent application Ser. Nos. 11/678,001, 11/678,016, and 11/804,585, each incorporated by reference herein in its entirety.

Referring to FIGS. **6**A-B, the assembly (A) that includes a sheath instrument **30** and a guide or catheter instrument **18** positioned over their respective mounting plates **38**, **37** is illustrated removed from the instrument driver **16**. The guide catheter instrument member **61***a* is coaxially interfaced with the sheath instrument member **62***a* by inserting the guide catheter instrument member **61***a* into a working lumen of the sheath catheter member **62***a*. As shown in FIG. **6**A, the sheath instrument **30** and the guide or catheter instrument **18** are coaxially disposed for mounting onto the instrument driver **16**. However, it should be understood that a sheath instrument **16** is used without a guide or catheter instrument **18**, or a guide or catheter instrument **18** is used without a sheath instrument **30** may be mounted onto the instrument driver **16** individually. With the coaxial arrangement as shown in FIG. **6**A, the guide catheter splayer **61** is located proximally relative to, or behind, the sheath splayer **62** such that the guide catheter member **61***a* can be inserted into and removed from the sheath catheter member **61***b*.

Examples of how sheath and guide splayers **62**, **61** may be structured are shown in FIGS. **7**-**7**F. FIG. **7** illustrates the sheath splayer **62** of one embodiment illustrated without a purge tube **32**. As shown in FIG. **6**A, the sheath and guide splayers **62**, **61**, appear similar physically in construction with the exception that the guide splayer **62** includes the purge tube **32**. It should be noted that the purge tube **32** may or may not be included for either the guide or sheath splayer. The sheath splayer **62** will be described herein. However it should be understood that the guide splayer **61** is of similar construction, and components of the sheath splayer **62** can be repeated for the guide splayer **61**.

As illustrated in FIG. **7**, the splayer **62** includes a splayer cover **72** fixably coupled to a splayer base assembly **78** using four screws **79**. The splayer base **78** having four cavities to receive and house pulley assemblies **80** is used for both the guide splayer **61** and sheath splayer **62**. For this embodiment of a sheath splayer **62**, two cavities of the splayer base **78** are populated with pulley assemblies **80** and the remaining cavities are left open. The guide splayer **61** may have all its cavities populated with four pulley assemblies **80**, as can be seen in FIG. **6**B. The splayer base **78** of this implementation can be constructed from injection molded polycarbonate.

One implementation uses substantially identical pulley assemblies **80** in both the guide and sheath splayers **61**,**62** which are illustrated in FIGS. **7**A-D. FIG. **7**A illustrates the full pulley assembly **80**. FIG. **7**B illustrates an exploded view of the pulley assembly **80**. Each pulley assembly **80** includes a top portion **82** and a bottom portion **84** held together with four screws **86** and four washers **88**. Note that in FIG. **7**B, only two screws **86** and two washers **88** are shown for clarity. Referring to FIG. **7**C, the top portion **82** of the pulley assembly **80** includes a stainless steel insert mold or drive shaft **90** with a drive pin **90***b*. The drive shaft **90** includes a flat portion **90***a* allowing it to form a D-shaped cross section. The bottom portion **84** includes four tapped holes **84***a* to receive the ends of the four screws **86** and also a wire securing slot **84***b*. As a pulley assembly **80** is put together and mated with a catheter pull wire or control element (not shown), the pull wire can be secured to the pulley assembly **80** by inserting the pull wire into the wire securing slot **84***b*. The pull wire (not shown) runs down the length of a catheter from distal to proximal end then is wound about the pulley. By rotating the pulley, the pull wire bends the distal tip of the catheter controlling its bend. The kinematics of robotically controlled catheters with pull wires will be described in further detail below.

FIG. **7**E illustrates the splayer cover **72** of one embodiment. The splayer cover **72** in this example includes a pair of latches **74** located on its inner surface. These latches are designed to engage with corresponding notches **38***b* located on the mounting plates **38** illustrated in FIG. **6**B. The splayer cover **72** also includes four holes **72***a* to receive the mounting screws **79** used to couple the splayer cover **72** to the splayer base assembly **78**. The splayer cover **72** and the latches **74** of this embodiment can be ABS molded. A pair of urethane based compliant members **82** located on the sides of the splayer cover **72** is over molded with the splayer cover **72** such that the splayer cover **72** is results as a single piece. Along opposing sides on the inside of the splayer cover **72** in this embodiment are two pairs of foam pads **84**. Each pair of foam pads **84** are located adjacent to the latch **74** and serve to provide its latch **74** some spring tension wherein better engagement between the splayer cover **72** and the mounting plate **38** can be achieved. In one implementation, a user can remove a splayer **62** mounted to an RCM by squeezing at the compliant member **82**, which in turn depress and disengage the latches **74** from the notches **38***b* of the RCM mounting plate **38**.

FIG. **7**F illustrates an exploded view of the splayer base assembly **78** of one embodiment which includes the splayer base **78**, a printed circuit assembly **94**, a set of magnets **96**, and a back panel **98**. During assembly of a splayer in accordance with some embodiments, the control cables of the catheter instrument are pre-tensioned by hand when the pulleys **80** are installed. Data related to individual catheter and splayer characteristics, including, but not limited to, full range of motion and critical parameters captured during the characterization process, are stored into a memory for later retrieval in the printed circuit assembly or PCA **94** which can act as a catheter identification (ID) programmable read-only memory (PROM). In alternative embodiments, other types non-volatile of memories such as flash memory or electrically programmable read-only memory (EPROM) can be used to store data. The PCA of this embodiment includes a pair of pogo pins **76** to detect contact with an RCM interface plate. The pogo pins **76** are positioned to make contact with the PCA **94** upon which the PROM is mounted as the splayer is placed onto the RCM mounting plate **38**. Also located on the underside of this splayer base assembly **78** are a pair of magnets **96**. In one embodiment, the magnets **96** are made of a neodymium material. As will be later described, the magnets are configured to be detected by read switches on the RCM interface to indicate splayer presence when a splayer is mounted on the RCM. The back panel **98** covers portions of the splayer base assembly **78**, which is also shown in FIG. **7**F. This back panel **98** includes openings for the pogo pins **76** to pass through.

Referring back to FIGS. **6**A-**6**B, when a catheter is prepared for use with an instrument, its splayer is mounted onto its appropriate interface plate. In this case, the sheath splayer **62** is placed onto the sheath interface plate **38** and the guide splayer **61** is place onto the guide interface plate **37**. In the illustrated example, each mounting plates **37**, **38** has four openings **37***a*, **38***a* that are designed to receive the corresponding drive shafts **90** attached to and extending from the pulley assemblies **80** of the splayers **61**, **62**. In the example illustrated in FIG. **6**B, two shafts **90** of the pulley assembly **80** are insertable within the right apertures or two openings **38***a* of the sheath interface plate **38** as the splayer **62** is mounted onto the RCM. Similarly, four shafts **90** of the guide splayer pulley assembly **80** are insertable within the four apertures or openings **37***a* of the guide interface plate **37**.

The RCM mounting plate in accordance with some embodiments includes a flex circuit with contacts and four read switches (not shown) for detecting the presence of a splayer and to indicate that a splayer has been mounted onto the interface plate. In some embodiments, the switches are also used to read the data from the memory. In alternative embodiments, various types of contacts and switches can be implemented to detect presence and/or access the PCA **94**. For this implementation, the switches are triggered by the magnets **96** of the splayer.

A user sets up the catheter by fastened it to the RCM initially. When the bottom surface of the splayer is within 180 thousandths of an inch from the interface plate, a magnetic field engages with the contact switches. The splayer **62**/**61** is mounted to an RCM, and the latches **73**,**74** are inserted through openings **38***b*,**37***b* on the mounting plate to latch onto the interface plate **38**,**37**, thus securely coupling the splayer **62**/**61** to the RCM. Once the splayer is engaged with the RCM, characterization parameters can be read from the PCA **94** by the RCM, allowing the RCM to set the splayer in its nominal position. In one embodiment, the data read from the PCA may include catheter length information, relative length information for zeroing up a sheath catheter and a guide catheter, and roll correction information. For example, the computer system may use the length information to initialize or configure the catheters for use by adjusting the guide catheter with respect to the guide catheter to ensure the catheters are zeroed up or that the guide catheter is located in a predefined position relative to the sheath catheter on the RCM. Similarly, the computer system may take the roll correction information, and roll off the catheter if any of the control wires are a bit offset or skewed, so that the catheter is oriented in the proper predefined direction (i.e., the 'up' direction on the catheter is really up). The data of one embodiment is gathered through bench testing during the manufacturing process and programmed into the PROM. In alternative embodiments, the data may have originated from a different part of the process. In one implementation, the PROM may also include a unique identifier or a code to prevent the catheter from being reused. The system of one embodiment is designed to recognize whether a catheter is brand new or whether it has already been used, and is capable of rejecting a previously used catheter. For this embodiment, the catheter is pre-tensioned through load sensing so that slack is removed from the control wires. The catheters are then prepared to be driven.

The sheath interface mounting plate **38** as illustrated in FIGS. **6**A and **6**B is similar to the guide interface mounting plate **37**, and thus, similar details are not repeated. One difference between the plates **37**, **38** may be the shape of the plates. For example, the guide interface plate **37** includes a narrow, elongated segment, which may be used with, for example, a dither mechanism. Both plates **37**, **38** include a plurality of openings **37***a*, **38***a* to receive drive shafts **90** and latches **73**,**74** from splayers **61**, **62**, respectively.

Referring back to FIG. **5**C the instrument driver **16** is illustrated with mounting plates **37**,**38** fixably coupled to a guide carriage **50**, and a sheath drive block **40**, respectively. FIG. **8**A illustrates the guide carriage **50** removed from the instrument driver **16** coupled to cabling **51** and associated guide motors **53**. The guide carriage **50** includes a funicular assembly **56** which is illustrated in FIG. **8**B. The funicular assembly **56** includes four sleeve receptacles **56***b*. As previously described, the drive shafts **90** of the splayer **61** (such as that shown in FIG. **5**B) first insert through the openings **37***a* in the mounting plate **37**. They then engage with the sleeve receptacles **56***b*. FIGS. **9**A-**9**B illustrate the shafts **90** of the splayer pulley assembly **61** engaging with the sleeve receptacles (**56***b*) in further detail. Referring back to FIG. **7**C, the drive shaft **90** has a flat edge **90***a* on one side of its cylindrical surface such that when the drive shaft **90** is viewed along its longitudinal axis, the shaft has the shape of a letter "D". It should be understood that the drive shaft **90** may include other cross-sectional shapes. The shaft **90** has an opening through which a cross pin **90***b* may be located. The drive shaft **90** may be keyed such that the shaft is designed to fit or be received within the receiving sleeve **56***b* having a certain shape. The sleeve **56***b* in the illustrated example includes a pair of V-shaped or wing shaped notches **56***c* to receive and hold the pin **90***b* of a shaft **90** as the shaft **90** is inserted into the sleeve **56***b*. In the illustrated example, the sleeve **56***b* does not employ capture pins, although such pins may be utilized.

Referring back to FIG. **8**A, a set of cables **51** wound around a set of pulleys **52**, are coupled on one end to a set of guide motors **53** and the other end to the sleeve receptacles **56***b*. The drive motors **53** are actuated to rotationally drive the sleeves **56***b*. A catheter assembly **30** with its splayer **61** mounted onto the instrument drive **16** would have its pulley assemblies **80** positioned inside a plurality of corresponding sleeves **56***b*. As the sleeves **56***b* are rotated, the pins **90***b* of the shafts **90** are seated in the V-shaped notches **56***c* and are engaged by the rotating sleeves **56***b*, thus causing the shafts **90** and associated pulley assemblies **80** to also rotate. The pulley assemblies **80** in turn cause the control elements (e.g., wires) coupled thereto to manipulate the distal tip of the catheter instrument **30** member in response thereto. To remove a splayer from the instrument driver in this implementation, less force is needed as the V-shaped notches **56***c* allow for quick and easy disengagement of the shafts **90** from the sleeves **56***b*.

FIGS. **10**A and **10**B illustrate perspective views of the sheath block **40** and motor driven interfaces **42** which are coupled to sheath articulation motors **43**. The sheath articulation motors **43** are coupled the motor driven interfaces **42** which includes a set of belts, shafts, and gears which drive receptacle sleeves **56***b* (which are similar in construction and functionality to the receptacle sleeves previously described for the guide funicular assembly). When the sheath splayer drive shafts **90** are coupled to the receptacle sleeves **56***b*, the sheath articulation motors **43** drive the receptacle sleeves **56***b* causing the sheath instrument **30** to bend.

During use, the catheter instrument **18** is inserted within a central lumen of the sheath instrument **30** such that the instruments **18**, **30** are arranged in a coaxial manner as previously described. Although the instruments **18**, **30** are arranged coaxially, movement of each instrument **18**, **30** can be controlled and manipulated independently. For this purpose, motors within the instrument driver **16** are controlled such that the drive and sheath carriages coupled to the mounting plates **37**, **38** are driven forwards and backwards independently on linear bearings each with leadscrew actuation. FIG. **10** illustrates the sheath drive block **40** removed from the instrument driver coupled to two independently-actuated lead screw **45**, **46** mechanisms driven by insert motors **47**. Note only the guide insert motor **47** is shown. The sheath insert motor is not shown in FIG. **10**. In the illustrated embodiment, the sheath insertion motor is coupled to a drive or output shaft (not shown) that is designed to move the sheath articulation assembly forwards and backwards, thus sliding a mounted sheath catheter instrument **18** forwards and backwards. The insert motion of the guide carriage can be actuated with a similar motorized leadscrew configuration.

Referring back to FIGS. **1**, **2** and **6**A, in order to accurately steer a robotic sheath **62***a* or guide catheter **61***a* from an operator work station **2**, a control structure should be implemented which allows a user to send commands through input devices such as the pendant **8** or MID **12** that will result in desired motion of the sheath **62***a* and guide **61***a*. FIGS. **11**A-**11**H and **12**-**16** illustrate examples of a control structure, which are described in further detail in the applications previously incorporated by reference.

The kinematic relationships for many catheter instrument embodiments may be modeled by applying conventional mechanics relationships. In summary, a control-element-steered catheter instrument is controlled through a set of actuated inputs. In a four-control-element catheter instrument, for example, there are two degrees of motion actuation, pitch and yaw, which both have + and − directions. Other motorized tension relationships may drive other instruments, active tensioning, or insertion or roll of the catheter instrument. The relationship between actuated inputs and the catheter's end point position as a function of the actuated inputs is referred to as the "kinematics" of the catheter.

Referring to FIGS. **11**A-H, the basic kinematics of a catheter **120** with four control elements **122***a*, **122***b*, **122***c*, **122***d* is reviewed. The catheter **120** may be component **61***a* or component **62***a* in some embodiments. Referring to FIGS. **11**A-B, as tension is placed only upon the bottom control element **122***c*, the catheter bends downward, as shown in FIG. **11**A. Similarly, pulling the left control element **122***d* in FIGS. **11**C-D bends the catheter left, pulling the right control element **122***b* in FIGS. **11**E-F bends the catheter right, and pulling the top control element **122***a* in FIGS. **11**G-H bends the catheter up. As will be apparent to those skilled in the art, well-known combinations of applied tension about the various control elements results in a variety of bending configurations at the tip of the catheter member **120**. One of the challenges in accurately controlling a catheter or similar elongate member with tension control elements is the retention of tension in control elements, which may not be the subject of the majority of the tension loading applied in a particular desired bending configuration. If a system or instrument is controlled with various levels of tension, then losing tension, or having a control element in a slack configuration, can result in an unfavorable control scenario. As previously described, each of these control elements or pull wires can be wound around a pulley which is motor actuated within the instrument driver. Maintaining adequate tension with these pulleys can be important for accurate catheter control.

FIG. **12** illustrates one example of a control flow for basic catheter control. The operator enters a command to designate a desired tip position for the device via some input mechanism (a master input device, computer software, or other user interface, etc.). Next, one or more inverse kinematic algorithms compute a desired catheter configuration in order to achieve the commanded tip position. The inverse kinematic algorithm can be varied depending on the construction of the shapeable device. The desired catheter configuration is then fed to one or more catheter mechanics algorithm to compute the positioning element displacements necessary to achieve the desired catheter configuration. These positioning element commands are then provided to the robots control algorithms (or in some cases actuators in the robot that interface with positioning elements in the shapeable element).

Based upon the applied positioning element displacements, the actual (physical) catheter mechanics including any constraints and obstructions acting on the catheter determine the real configuration or shape that the shapeable device achieves. This is illustrated on the right (slave/actual) side of FIG. **12**. This real catheter configuration/shape determines the real catheter tip position. These kinematic relationships of the physical device are represented in the figure with a forward kinematics block **124**. Assuming that the operator is observing the catheter tip through some sort of visualization (fluoro, endoscopy, etc), the operator can then use this visual feedback to make corrections to the commanded tip position.

Referring to FIG. **13**, the "forward kinematics" expresses the catheter's end-point position as a function of the actuated inputs while the "inverse kinematics" expresses the actuated inputs as a function of the desired end-point position. In certain embodiments, accurate mathematical models of the forward and inverse kinematics are useful for the control of a robotically controlled catheter system. For clarity, the kinematics equations are further refined to separate out common elements, as shown in FIG. **13**. The basic kinematics describes the relationship between the task coordinates and the joint coordinates. In such case, the task coordinates refer to the position of the catheter end-point while the joint coordinates refer to the bending (pitch and yaw, for example) and length of the active catheter. The actuator kinematics describes the relationship between the actuation coordinates and the joint coordinates. The task, joint, and bending actuation coordinates for the robotic catheter are illustrated in FIG. **14**. By describing the kinematics in this way we can separate out the kinematics associated with the catheter structure, namely the basic kinematics, from those associated with the actuation methodology.

An inverse kinematic model translates intended device motion into the commands that will adjust the actuator and/or control element to position the shapeable instrument as desired. Referring back to FIG. **12**, the shapeable instrument kinematics are the mathematical relationships between the task space description of the instrument (e.g., tip position) and the configuration space description of the instrument (e.g., shape). Specifically, the inverse kinematics (task to configuration space) are used as part of the chain that translates desired tip positions into actuator commands (leading to displacements of the control elements) that move tip position of the actual device for reaching a desired tip position.

These inverse kinematic algorithms are derived based upon certain assumptions about how the shapeable instrument moves. Examples of these assumptions may include, but are not limited to: 1) Each catheter segment bends in a constant curvature arc; 2) Each catheter segment bends within a single plane; 3) Some catheter segments have fixed (constant) lengths; 4) Some catheter segments have variable (controllable) lengths.

In one variation, the development of the catheter's kinematics model is derived using a few assumptions. In one example, the included are assumptions that the catheter structure is approximated as a simple beam in bending from a mechanics perspective, and that control elements, such as thin tension wires, remain at a fixed distance from the neutral axis and thus impart a uniform moment along the length of the catheter.

In addition to the above assumptions, the geometry and variables shown in FIGS. **14** and **15** are used in the derivation of the forward and inverse kinematics. The basic forward kinematics, relating the catheter task coordinates (X_c, Y_c, Z_c) to the joint coordinates (ϕ_{yaw}, ϕ_{pitch}, L), is given as follows:

$$X_c=\omega\cos(\theta)$$

$$Y_c=R\sin(\alpha)$$

$$Z_c=\omega\sin(\theta)$$

Where

$$w=R(1-\cos(\alpha))$$

$$\alpha=[(\phi_{pitch})^2+(\phi_{yaw})^2]^{1/2}\text{ (total bending)}$$

$$R=\frac{L}{\alpha}\text{(bend radius)}$$

$$\theta=a\tan 2(\phi_{pitch},\phi_{yaw})\text{ (roll angle)}$$

The actuator forward kinematics, relating the joint coordinates (ϕ_{yaw}, ϕ_{pitch}, L) to the actuator coordinates (ΔL_x, ΔL_z, L) is given as follows:

$$\phi_{pitch}=(2\Delta L_2)/D_c$$

$$\phi_{yaw}=\frac{2\Delta L_x}{D_c}$$

As illustrated in FIG. **13**, the catheter's end-point position can be predicted given the joint or actuation coordinates by using the forward kinematics equations described above.

Calculation of the catheter's actuated inputs as a function of end-point position, referred to as the inverse kinematics, can be performed numerically, using a nonlinear equation solver such as Newton-Raphson. In another approach, shown in the illustrative embodiment, is to develop a closed-form solution which can be used to calculate the required actuated inputs directly from the desired end-point positions.

As with the forward kinematics, we separate the inverse kinematics into the basic inverse kinematics, which relates joint coordinates to the task coordinates, and the actuation inverse kinematics, which relates the actuation coordinates to the joint coordinates. The basic inverse kinematics, relating the joint coordinates (ϕ_{yaw}, ϕ_{pitch}, L), to the catheter task coordinates (Xc, Yc, Zc) is given as follows:

$$\phi_{pitch}=\alpha\sin(\theta)$$

$$\phi_{yaw}=\alpha\cos(\theta)$$

$$L=R\alpha$$

$$\begin{array}{ccc} & \theta=\operatorname{atan2}(Z_c,X_c) & \beta=\operatorname{atan2}(Y_c,W_c) \\ \to\text{where}\to\ \to & R=\dfrac{l\sin\beta}{\sin 2\beta} & \to\ W_c=(X_c^2+Z_c^2)^{1/2} \\ & \alpha=\pi-2\beta & l=(W_c^2+Y_c^2)^{1/2} \end{array}$$

The actuator inverse kinematics, relating the actuator coordinates (ΔL_x, ΔL_z, L) to the joint coordinates (ϕ_{yaw}, ϕ_{pitch}, L) is given as follows:

$$\Delta L_x=\frac{D_c\phi_{yaw}}{2}$$

$$\Delta L_2=\frac{D_c\phi_{pitch}}{2}$$

In one embodiment, the catheter (or other shapeable instrument) is controlled in an open-loop manner as shown in FIG. **16**. In this type of open loop control model, the shape configuration command comes in to the beam mechanics, is translated to beam moments and forces, then is translated to tendon tensions given the actuator geometry, and finally into tendon displacement given the entire deformed geometry. However, there are numerous reasons why the assumed motion of the catheter may not match the actual motion of the catheter. One important factor is the presence of unanticipated or unmodeled constraints imposed by the patient's anatomy.

Accordingly, a control system that directs catheters or shapeable instruments can command joint configurations that can achieve a desired tip position. However, the presence of modeling inaccuracies and environment interaction causes a differential between the actual position from that intended. A simple tip position can quantify this error, but addressing the source of the error requires the additional information regarding the shapeable instrument. Data defining the actual or real shape of the instrument can provide much of this information.

The term "localization" is used in the art in reference to systems for determining and/or monitoring the position of objects, such as medical instruments, in a reference coordinate system. In one embodiment, the instrument localization software is a proprietary module packaged with an off-the-shelf or custom instrument position tracking system, which may be capable of providing not only real-time or near real-time positional information, such as X-Y-Z coordinates in a Cartesian coordinate system, but also orientation information relative to a given coordinate axis or system. For example, such systems can employ an electromagnetic based system (e.g., using electromagnetic coils inside a device or catheter body). Other systems utilize potential difference or voltage, as measured between a conductive sensor located on the pertinent instrument and conductive portions of sets of patches placed against the skin, to determine position and/or orientation. In another similar embodiment, one or more conductive rings may be electronically connected to a potential-difference-based localization/orientation system, along with multiple sets, preferably three sets, of conductive skin patches, to provide localization and/or orientation data. Additionally, "Fiberoptic Bragg grating" ("FBG") sensors may be used to not only determine position and orientation data but also shape data along the entire length of a catheter or shapeable instrument.

In other embodiments not comprising a localization system to determine the position of various components, kinematic and/or geometric relationships between various components of the system may be utilized to predict the position of one component relative to the position of another. Some embodiments may utilize both localization data and kinematic and/or geometric relationships to determine the positions of various components. The use of localization and shape technology is disclosed in detail in U.S. patent application Ser. Nos. 11/690,116, 11/176,598, 12/012,795, 12/106,254, 12/507,727, 12/822,876, 12/823,012, and 12/823,032, the entirety of all of which is incorporated by reference herein for all purposes.

To accurately coordinate and control actuations of various motors within an instrument driver from a remote operator control station such as that depicted in FIG. **1**, an advanced computerized control and visualization system is preferred. The control system embodiments that follow are described in reference to a particular control systems interface, namely the SimuLink™ and XPC™ control interfaces available from The Mathworks Inc., and PC-based computerized hardware configurations. However, one of ordinary skilled in the art having the benefit of this disclosure would appreciate that many other control system configurations may be utilized, which may include various pieces of specialized hardware, in place of more flexible software controls running on one or more computer systems.

Referring to FIG. **17**, an overview of an embodiment of a controls system flow is depicted. A master computer **400** running master input device software, visualization software, instrument localization software, and software to interface with operator control station buttons and/or switches is depicted. In one embodiment, the master input device software is a proprietary module packaged with an off-the-shelf master input device system, such as the Phantom™ from Sensible Devices Corporation, which is configured to communicate with the Phantom™ hardware at a relatively high frequency as prescribed by the manufacturer. Other suitable master input devices, such as the master input device **12** depicted in FIG. **2** are available from suppliers such as Force Dimension of Lausanne, Switzerland. The master input device **12** may also have haptics capability to facilitate feedback to the operator, and the software modules pertinent to such functionality may also be operated on the master computer **126**.

Referring to FIG. **17**, in one embodiment, visualization software runs on the master computer **126** to facilitate real-time driving and navigation of one or more steerable instruments. In one embodiment, visualization software provides an operator at an operator control station, such as that depicted in FIG. **2**, with a digitized "dashboard" or "windshield" display to enhance instinctive drivability of the pertinent instrumentation within the pertinent tissue structures. Referring to FIG. **18**, a simple illustration is useful to explain one embodiment of a preferred relationship between visualization and navigation with a master input device **12**. In the depicted embodiment, two display views **142**, **144** are shown. One preferably represents a primary **142** navigation view, and one may represent a secondary **144** navigation view. To facilitate instinctive operation of the system, it is preferable to have the master input device coordinate system at least approximately synchronized with the coordinate system of at least one of the two views. Further, it is preferable to provide the operator with one or more secondary views which may be helpful in navigating through challenging tissue structure pathways and geometries.

Referring still to FIG. **18**, if an operator is attempting to navigate a steerable catheter in order to, for example, contact a particular tissue location with the catheter's distal tip, a useful primary navigation view **142** may comprise a three dimensional digital model of the pertinent tissue structures **146** through which the operator is navigating the catheter with the master input device **12**, along with a representation of the catheter distal tip location **148** as viewed along the longitudinal axis of the catheter near the distal tip. This embodiment illustrates a representation of a targeted tissue structure location **150**, which may be desired in addition to the tissue digital model **146** information. A useful secondary view **144**, displayed upon a different monitor, in a different window upon the same monitor, or within the same user interface window, for example, comprises an orthogonal view depicting the catheter tip representation **148**, and also perhaps a catheter body representation **152**, to facilitate the operator's driving of the catheter tip toward the desired targeted tissue location **150**.

In one embodiment, subsequent to development and display of a digital model of pertinent tissue structures, an operator may select one primary and at least one secondary view to facilitate navigation of the instrumentation. By selecting which view is a primary view, the user can automatically toggle a master input device **12** coordinate system to synchronize with the selected primary view. In an embodiment with the leftmost depicted view **142** selected as the primary view, to navigate toward the targeted tissue site **150**, the operator should manipulate the master input device **12** forward, to the right, and down. The right view will provide valued navigation information, but will not be as instinctive from a "driving" perspective.

To illustrate: if the operator wishes to insert the catheter tip toward the targeted tissue site **150** watching only the rightmost view **144** without the master input device **12** coordinate system synchronized with such view, the operator would have to remember that pushing straight ahead on the master input device will make the distal tip representation **148** move to the right on the rightmost display **144**. Should the operator decide to toggle the system to use the rightmost view **144** as the primary navigation view, the coordinate system of the master input device **12** is then synchronized with that of the rightmost view **144**, enabling the operator to move the catheter tip **148** closer to the desired targeted tissue location **150** by manipulating the master input device **12** down and to the right. The synchronization of coordinate systems may be conducted using fairly conventional mathematic relationships which are described in detail in the aforementioned applications incorporated by reference.

Referring back to embodiment of FIG. **17**, the master computer **126** also comprises software and hardware interfaces to operator control station buttons, switches, and other input devices which may be utilized, for example, to "freeze" the system by functionally disengaging the master input device as a controls input, or provide toggling between various scaling ratios desired by the operator for manipulated inputs at the master input device **12**. The master computer **126** has two separate functional connections with the control and instrument driver computer **128**: one connection **132** for passing controls and visualization related commands, such as desired XYZ (in the catheter coordinate system) commands, and one connection **134** for passing safety signal commands. Similarly, the control and instrument driver computer **128** has two separate functional connections with the instrument and instrument driver hardware **130**: one connection **136** for passing control and visualization related commands such as required-torque-related voltages to the amplifiers to drive the motors and encoders, and one connection **138** for passing safety signal commands.

Also shown in the signal flow overview of FIG. **17** is a pathway **140** between the physical instrument and instrument driver hardware **130** back to the master computer **126** to depict a closed loop system embodiment wherein instrument localization technology, previously described, is utilized to determine the actual position of the instrument to minimize navigation and control error, as described in further detail below.

FIGS. **19**A-K depict various aspects of one embodiment of a SimuLink™ software control schema for an embodiment of the physical system, with particular attention to an embodiment of a "master following mode." In this embodiment, an instrument is driven by following instructions from a master input device, and a motor servo loop embodiment, which comprises key operational functionality for executing upon commands delivered from the master following mode to actuate the instrument.

FIG. **19** depicts a high-level view of an embodiment wherein any one of three modes may be toggled to operate the primary servo loop **154**. In idle mode **156**, the default mode when the system is started up, all of the motors are commanded via the motor servo loop **154** to servo about their current positions, their positions being monitored with digital encoders associated with the motors. In other words, idle mode **156** deactivates the motors, while the remaining system stays active. Thus, when the operator leaves idle mode, the system knows the position of the relative components. In auto home mode **158**, cable loops within an associated instrument driver, such as that depicted in FIG. **5**A-5C, are centered within their cable loop range to ensure substantially equivalent range of motion of an associated instrument in both directions for a various degree of freedom, such as + and − directions of pitch or yaw, when loaded upon the instrument driver. This is a setup mode for preparing an instrument driver before an instrument is engaged.

In master following mode **160**, the control system receives signals from the master input device, and in a closed loop embodiment from both a master input device and a localization system, and forwards drive signals to the primary servo loop **154** to actuate the instrument in accordance with the forwarded commands. Aspects of the primary servo loop and motor servo block **162** are depicted in further detail in FIGS. **20-23**.

Referring to FIG. **24**, a more detailed functional diagram of an embodiment of master following mode **160** is depicted. As shown in FIG. **24**, the inputs to functional block **170** are XYZ position of the master input device in the coordinate system of the master input device which, per a setting in the software of the master input device may be aligned to have the same coordinate system as the catheter, and localization XYZ position of the distal tip of the instrument as measured by the localization system in the same coordinate system as the master input device and catheter. Referring to FIG. **25** for a more detailed view of functional block **170** of FIG. **24**, a switch **186** is provided to allow switching between master inputs for desired catheter position, to an input interface **188** through which an operator may command that the instrument go to a particular XYZ location in space. Various controls features may also utilize this interface to provide an operator with, for example, a menu of destinations to which the system should automatically drive an instrument, etc. Also depicted in FIG. **25** is a master scaling functional block **184** which is utilized to scale the inputs coming from the master input device with a ratio selectable by the operator. The command switch **186** functionality includes a low pass filter to weight commands switching between the master input device and the input interface **188**, to ensure a smooth transition between these modes.

Referring back to FIG. **24**, desired position data in XYZ terms is passed to the inverse kinematics block **174** for conversion to pitch, yaw, and extension (or "insertion") terms in accordance with the predicted mechanics of materials relationships inherent in the mechanical design of the instrument. The pitch, yaw, and extension commands are passed from the inverse kinematics **174** to a position control block **172** along with measured localization data. FIG. **29** provides a more detailed view of the position control block **172**. After measured XYZ position data comes in from the localization system, it goes through a inverse kinematics block **189** to calculate the pitch, yaw, and extension the instrument needs to have in order to travel to where it needs to be. Comparing **191** these values with filtered desired pitch, yaw, and extension data from the master input device, integral compensation is then conducted with limits on pitch and yaw to integrate away the error. In this embodiment, the extension variable does not have the same limits **193**, as do pitch and yaw **195**. As will be apparent to those skilled in the art, having an integrator in a negative feedback loop forces the error to zero. Returning to FIG. **24**, desired pitch, yaw, and extension commands are next passed through a catheter workspace limitation **176**, which may be a function of the experimentally determined physical limits of the instrument beyond which componentry may fail, deform undesirably, or perform unpredictably or undesirably. This workspace limitation defines a volume similar to a cardioid-shaped volume about the distal end of the instrument. Desired pitch, yaw, and extension commands, limited by the workspace limitation block, are then passed to a catheter roll correction block **178**.

This functional block is depicted in further detail in FIG. **26**, and comprises a rotation matrix for transforming the pitch, yaw, and extension commands about the longitudinal, or "roll", axis of the instrument—to calibrate the control system for rotational deflection at the distal tip of the catheter that may change the control element steering dynamics. For example, if a catheter has no rotational deflection, pulling on a control element located directly up at twelve o'clock should urge the distal tip of the instrument upward. If, however, the distal tip of the catheter has been rotationally deflected by, say, ninety degrees clockwise, to get an upward response from the catheter, it may be necessary to tension the control element that was originally positioned at a nine o'clock position. The catheter roll correction schema depicted in FIG. **26** provides a means for using a rotation matrix to make such a transformation, subject to a roll correction angle, such as the ninety degrees in the above example, which is input, passed through a low pass filter, turned to radians, and put through rotation matrix calculations.

In one embodiment, the roll correction angle is determined through experimental experience with a particular instrument and path of navigation. In another embodiment, the roll correction angle may be determined experimentally in-situ using the accurate orientation data available from the preferred localization systems. In other words, with such an embodiment, a command to, for example, bend straight up can be executed, and a localization system can be utilized to determine at which angle the defection actually went—to simply determine the in-situ roll correction angle.

Referring briefly back to FIG. **24**, roll corrected pitch and yaw commands, as well as unaffected extension commands, are output from the roll correction block **178** and may optionally be passed to a conventional velocity limitation block **180**. Referring to FIG. **27**, pitch and yaw commands are converted from radians to degrees, and automatically controlled roll may enter the controls picture to complete the current desired position **190** from the last servo cycle. Velocity is calculated by comparing the desired position from the previous servo cycle, as calculated with a conventional memory block (**192**) calculation, with that of the incoming commanded cycle. A conventional saturation block **187** keeps the calculated velocity within specified values, and the velocity-limited command **194** is converted back to radians and passed to a tension control block **182**.

Tension within control elements may be managed depending upon the particular instrument embodiment, as described above in reference to the various instrument embodiments and tension control mechanisms. As an example, FIG. **28** depicts a pre-tensioning block **196** with which a given control element tension is ramped to a present value. An adjustment is then added to the original pre-tensioning based upon a preferably experimentally-tuned matrix pertinent to variables, such as the failure limits of the instrument construct and the incoming velocity-limited pitch, yaw, extension, and roll commands. This adjusted value is then added **198** to the original signal for output, via gear ratio adjustment, to calculate desired motor rotation commands for the various motors involved with the instrument movement. In this embodiment, extension, roll, and sheath instrument actuation **199** have no pre-tensioning algorithms associated with their control. The output is then complete from the master following mode functionality, and this output is passed to the primary servo loop **154**.

Referring back to FIG. **19**, incoming desired motor rotation commands from either the master following mode **160**, auto home mode **158**, or idle mode **156** in the depicted embodiment are fed into a motor servo block **162**, which is depicted in greater detail in FIGS. **20-23**.

Referring to FIG. **20**, incoming measured motor rotation data from digital encoders and incoming desired motor rotation commands are filtered using conventional quantization noise filtration **164** at frequencies selected for each of the incoming data streams to reduce noise while not adding undue delays which may affect the stability of the control system. As shown in FIGS. **22** and **23**, conventional quantization filtration is utilized on the measured motor rotation signals at about 200 hertz in this embodiment, and on the desired motor rotation command at about 15 hertz. The difference **166** between the quantization filtered values forms the position error which may be passed through a lead filter, the functional equivalent of a proportional derivative ("PD")+ low pass filter. In another embodiment, conventional PID, lead/lag, or state space representation filter may be utilized. The lead filter of the depicted embodiment is shown in further detail in FIG. **21**.

In particular, the lead filter embodiment in FIG. **21** comprises a variety of constants selected to tune the system to achieve desired performance. The depicted filter addresses the needs of one embodiment of a 4-control element guide catheter instrument with independent control of each of four control element interface assemblies for .+−.pitch and .+−.yaw, and separate roll and extension control. As demonstrated in the depicted embodiment, insertion and roll have different inertia and dynamics as opposed to pitch and yaw controls, and the constants selected to tune them is different. The filter constants may be theoretically calculated using conventional techniques and tuned by experimental techniques, or wholly determined by experimental techniques, such as setting the constants to give a sixty degree or more phase margin for stability and speed of response, a conventional phase margin value for medical control systems.

In an embodiment where a tuned master following mode is paired with a tuned primary servo loop, an instrument and instrument driver, such as those described above, may be "driven" accurately in three-dimensions with a remotely located master input device. Other preferred embodiments incorporate related functionalities, such as haptic feedback to the operator, active tensioning with a split carriage instrument driver, navigation utilizing direct visualization and/or tissue models acquired in-situ and tissue contact sensing, and enhanced navigation logic.

I-A. Insertion Force Indicator

Referring to FIGS. **30-31**, a further embodiment is directed systems and methods for indicating catheter **61***a* insertion forces. When the guide catheter **61***a* extends from the sheath **62***a* and makes contact with tissue, a certain force F is imparted onto the guide catheter **61***a*. Depending on how far the distal tip **92** of the guide catheter **61***a* is extended from the sheath **62***a*, the force F may result in different interactions between the guide catheter **61***a* and tissue.

In one variation as illustrated in FIG. **30**, a length L_1 of the guide catheter instrument **61***a* extends beyond the distal tip **91** of the sheath **62***a*. As the distal tip **92** of the guide catheter **61***a* makes contact with tissue with a force F, an equal and opposite force F is imparted to the guide catheter instrument **61***a* (represented by arrow F). Depending upon the magnitude of the force F, a portion of the guide catheter **61***a*, e.g., adjacent to the distal tip **92**, may be caused to bend, flex or buckle under the force F, thereby reducing the force exerted on the tissue.

FIG. **31** illustrates a guide catheter **61***a* that extends a shorter length L_2 beyond the distal tip **91** of the sheath **62***a*. In this example, when the distal tip **92** of the guide catheter **61***a* makes contact with tissue with the same force F, the shorter length L**2** reduces or eliminates flexing since the distal portion of the guide catheter **61***a* is reinforced by the distal end of the stiffer sheath **62***a*, resulting in a larger force F that is applied to the tissue due to less flexing.

In one system (S), motors of the instrument driver **16** are controlled to robotically control and manipulate catheter instruments **18**. The amount of current supplied to the motor is proportionally related to the amount of torque generated by the motors and catheter **18** insertion force is proportional to the motor torque. Thus, the motor current is proportional to the insertion force. If the motors are driven by the same amount of current regardless of how far the guide catheter **61***a* extends out from the sheath **62***a*, the force imparted on the tissue at the contact point may differ based on length L. For example, if a high motor current causes a high insertion force for a guide catheter **61***a* extending length L_1, the catheter **61***a* may dissipate a portion of that force due to flexing or bending. However, when the guide catheter **61***a* extends a much smaller length L_2, it may not yield, and the insertion force is not attenuated. In one embodiment, a kinematic model of the instrument configuration may be utilized, in concert with sensed motor torques at driveshafts within the instrument driver, to calculate, or "back out", the loads and vectors thereof that are theoretically applied to the distal end of the instrument, or other portion of the instrument in contact with an external load-applying structure.

In one embodiment, a system (S) may be configured to generate a visual or audible warning message to a user, control element or processor indicating that corrective action is required and/or to indicate a possibility of high insertion forces exerted to tissue at the distal tip **92**. In one embodiment, a warning message is displayed when length L is less than a minimum length L_{min} and/or the motor current I is greater than I_{max}. For example, the minimum length L_{min} may be about 30 mm or less, and the maximum motor current I_{max} may be about 250 mA or higher current levels. In cases in which the length or motor current exceeds these pre-determined values, the operator may adjust the motor current accordingly or proceed carefully to avoid causing injury. This type of force indication message may be useful for instrument driver **16** that do not have force sensing capabilities.

I-B. Reachability/Viewability

Another alternative embodiment is directed to methods and systems for assessing reachability and viewability at a particular location. More particularly, embodiments advantageously assess locations within the body that can be reached by a catheter instrument **18** of the system (S), as well as assessing the viewability or field of view at a particular location that can be reached by the catheter instrument **18**. This ability is particularly significant since the field of view at a particular location may not be desirable even if it is reachable. Thus, embodiments advantageously assess field of view at reachable locations in order to provide more meaningful surgical planning and results.

For example, in the context of cardiac surgery utilizing an intracardiac (ICE) catheter. During the planning stage, an operator can determine offline before a procedure where a catheter should be driven to provide for a desired field of view that allows a region of interest to be scanned. Alternatively, a previously acquired CT model may be registered and fused with real time ultrasound data during a surgical procedure. During use, embodiments allow the ICE catheter to be driven to a position within the heart with a desired or optimum field of view for scanning of, e.g., the left atrium, or another internal tissue or segment thereof that is of interest.

Referring to FIG. **32**, in one embodiment, a robotic medical system includes an outer sheath **62***a* with a working lumen, and an inner guide catheter **61***a* extending through the sheath lumen, with a distal end portion of the guide catheter **61***a* extending out a distal end opening of the sheath **62***a* in an anatomic workspace **116** in a body. An intracardiac (ICE) ultrasound imaging catheter **112** is positioned in a working lumen of the guide catheter **61***a*, with a distal end portion of the ICE catheter **112** extending out a distal end opening of the guide catheter **61***a*. The ICE catheter **112** may be extended out of, and retracted into, respectively, the distal end opening in the guide catheter **61***a*, as indicated by arrow **115**A, and may be rotated about its longitudinal axis, as indicated by arrow **115**B, such that a transducer array **113** on the ICE catheter **112** is positionable within the anatomic workspace **116** to capture ultrasound images within a field of view **114** of the array **113**. The depicted ICE catheter **112** comprises a substantially linear array **113** defining a field of view **114** having a substantially trapezoidal shape; ICE catheters with such configurations are available from suppliers such as the Ultrasound division of Siemens AG under the tradename AcuNav™. In other embodiments, substantially circular/disc shaped fields of view may be created utilizing an ultrasound transducer configuration which may be rotated along with a portion of the ICE catheter with a drive shaft, as in the ICE catheters available from Boston Scientific, or utilizing multiple ultrasound transducers placed circumferentially around a catheter body, as in the ultrasound imaging catheters available from Volcano Corporation. For illustrative purposes, FIG. **32** depicts a linear array, AcuNav™ type configuration—but each of the aforementioned other configurations may be similarly employed.

Depending on factors such as the anatomical boundaries and tissue structures in the anatomical workspace **116**, and the relative positions and prior trajectories of the sheath **62***a*, guide catheter **61***a*, and ICE catheter **112** within the workspace **116**, the system controller (not shown in FIG. **32**) can model the potential relative movement the respective sheath **62***a*, guide **61***a*, and ICE catheter **112**, and thus the potential movement of the field of view **114** of the transducer array **113** within the work space **116**. In particular, certain tissue walls and/or structures within the anatomic workspace **116** can be readily imaged (or "viewable") by the ICE transducer **113** without requiring anything more than a relatively simple repositioning of the respective sheath **62***a*, guide **61***a*, and ICE catheter **112**, respectively, such as tissue structure **117** in FIG. **21**. Other tissue wall locations and/or structures may be viewable, but only by more complicated maneuvering techniques, including iterative movements of one or more of the sheath **62***a*, guide **61***a*, and/or ICE catheter **112**, respectively, in order to position the transducer **113** and field of view **114**, such as tissue structure **118** in FIG. **32**. Still further tissue wall locations and/or structures may be difficult or impossible to capture within the field of view **114** of the ICE transducer **113** without a major repositioning of the collective instruments (sheath **62***a*, guide **61***a*, ICE catheter **112**), if at all.

This "ICE viewability" analysis may be useful for both pre-operative planning, and during a procedure, wherein the robotic system controller is configured to determine a respective reach of the distal end portion of the ICE catheter **112**, and thus the potential fields of view **114** that may be captured by the transducer array **113** within the anatomical workspace **116**, based at least in part upon a planned or a present relative position of the respective sheath **62***a*, guide **61***a*, and ICE catheter **112** instruments. By way of non-limiting examples, the controller may determine the viewability of the various anatomic wall surfaces and/or tissue structures based at least in part on a kinematic model of one or both of the sheath and guide catheter instruments **62***a* and **61***a*. Further, the controller may display the possible field of views, viewable tissue walls and/or structures, or both, overlaying an image of the anatomic workspace on a display associated with the robotic system, wherein the image of the anatomic workspace is obtained from a model of the workspace, from an imaging system, or both.

While various embodiments haven been described herein, such disclosure is provided for purposes explanation and illustration. Further, various embodiments may be used in combination with other embodiments. Additionally, although certain embodiments are described with reference to particular dimensions or parameters, it should be understood that these dimensions and parameters are provided for purposes of explanation, and that other dimensions and parameters may also be utilized.

Embodiments and instruments of robotic systems (S) may be used in various minimally invasive surgical procedures that involve different types of tissue including heart, bladder and lung tissue, for example. Depending on the procedure, distal portions of various instruments may not be easily visible to the naked eye. Various imaging modalities including magnetic resonance (MR), ultrasound, computer tomography (CT), X-ray, fluoroscopy, etc. may be used for this purpose to visualize the surgical procedure and location of instruments. Further, it may be desirable to know the precise location of a given catheter instrument and/or working tool at any given moment to avoid undesirable contacts or movements. For this purpose, one or more localization techniques that are presently available may be applied to any of the apparatuses and methods disclosed above. For example, one or more localization coils may be built into a flexible catheter instrument. In other implementations, a localization technique using radio-opaque markers may be used with embodiments of the present invention. Similarly, a fiber optic Bragg sensing fiber may be built into the sidewall of a catheter instrument to sense position and temperature. Embodiments may also be implemented in systems that include a plurality of sensors, including those for sensing patient vitals, temperature, pressure, fluid flow, force, etc., may be combined with the various embodiments of flexible catheters and distal orientation platforms disclosed herein.

Embodiments of flexible catheters and other related instruments used in a robotic surgical system may be made of various materials, including materials and associated techniques that are the same as or similar to those described in U.S. patent application Ser. No. 11/176,598, the contents of which were previously incorporated by reference. For example, suitable materials may include stainless steel, copper, aluminum, nickel-titanium alloy (Nitinol), Flexinol™ (available from Toki of Japan), titanium, platinum, iridium, tungsten, nickel-chromium, silver, gold, and combinations thereof, may be used to manufacture parts such as control elements, control cables, spine elements, gears, plates, ball units, wires, springs, electrodes, thermocouples, etc. Similarly, non-metallic materials including, but not limited to, polypropylene, polyurethane (Pebax™), nylon, polyethylene, polycarbonate, Delrin™, polyester, Kevlar™, carbon, ceramic, silicone, Kapton™ polyimide, Teflon™ coating, polytetrafluoroethylene (PTFE), plastic (non-porous or porous), latex, polymer, etc. may be used to make the various parts of a catheter and other system components.

Further, although embodiments are describe with reference to a catheter in the form of a guide catheter and working instruments, it is also contemplated that one or more lumens of catheters may be used to deliver fluids such as saline, water, carbon dioxide, nitrogen, helium, for example, in a gaseous or liquid state, to the distal tip. Furthermore, it is contemplated that some embodiments may be implemented with a open loop or closed loop cooling system wherein a fluid is passed through one or more lumens in the sidewall of the catheter instrument to cool the catheter or a tool at the distal tip.

Further, although various embodiments are described with reference to a sheath and/or a guide catheter having four control elements or pull wires, it may be desirable to have a guide instrument with different numbers of control elements, e.g., less than four control elements. Further, although certain embodiments are described with reference to a guide catheter in combination with a steerable sheath, other embodiments may be implemented in systems that include a guide catheter (or other catheter) in combination with a pre-bent, unsteerable sheath, or perhaps with no sheath at all. Further, embodiments described above may be utilized with manually or robotically steerable instruments, such as those described in U.S. patent application Ser. No. 11/481,433, incorporated herein by reference. The instrument driver can be configured and adapted to meet the needs of different system and instrument configurations, e.g., using different numbers of motors and gearboxes for driving control elements, or variation in the configuration for actuating a given control element interface assembly, and associated variation in the tensioning mechanism and number of control element pulleys associated with the pertinent control element interface assembly (one pulley and one cable per control element interface assembly, two pulleys and two cables per control element interface assembly, slotted, split carriage, and winged split carriage embodiments, various tensioning embodiments, etc.

II. Catheter

FIG. **33**A illustrates a cross-sectional view of a section or portion of a flexible and steerable elongate instrument or catheter **300** of an instrument assembly in accordance with some embodiments. The catheter **300** may be coupled to the drivable assembly **182** in some embodiments. The steerable elongate instrument **300** may be substantially pliable or flexible such that when it is advanced into a patient, an operator or surgeon may easily manipulate the instrument **300** to conform, adopt, or match the shape or curvatures of the internal pathways (e.g., gastrointestinal tract, blood vessels, etc.) of the patient. As illustrated, the flexible and steerable elongate instrument or catheter **300** may be comprised of multiple layers of materials and/or multiple tube structures. For example, the elongate instrument **300** may include an outer layer or outer tube **302**, a main lumen, primary lumen, or central lumen **318** defined by an inner layer or inner tube **312**, and minor, secondary, or peripheral lumens incorporated in the body of the elongate instrument **300** substantially between the outer layer **302** and the inner layer **312** where operational tubes **304**, flexible tubes **306**, push tubes **308**, and support tubes **310** are disposed or contained. The lumen **318** may be used to deliver one or more surgical instruments or tools from the proximal portion of the elongate instrument **300** to the distal portion of the elongate instrument **300** where they may be positioned and used to treat a target tissue structure inside a patient. The outer layer or outer tube **302** and the inner layer or inner tube **312** may be made of any flexible, pliable, or suitable polymer material or bio-compatible polymer material (e.g., nylon-12, Pebax®, Pellathane, Polycarbonate, etc.) or braided plastic composite structure. In some embodiments, outer layer or outer tube **302** and the inner layer or inner tube **312** may be one layer of material or one tube structure instead of separate layers of material or separate tube structures. Operational tubes **304** may not be actual tubes but may be the minor, secondary, or peripheral lumens or channels through the body of the outer layer or outer tube **302** or the operational tubes **304** may be separate operational tube structures that are disposed inside the minor, secondary, or peripheral lumens or channels in the body structure of the outer layer or outer tube **302**. The operational tubes **304** may be made of any suitable polymer material, bio-compatible polymer material or metallic material (e.g., polyimide, stainless steel or spiral cut stainless steel, Nitinol, etc.). The separate operational tubes **304** may be melted and/or braided into the wall of the minor, secondary, or peripheral lumens of the outer tube **302** or inner tube **312**. The operational tubes **304** may provide a substantially slidable surface and interface for the flex tubes **306**, such that the flex tubes **306** may slide substantially freely about the interior of the operational tubes **304** in a substantially decoupled configuration. In some embodiments, a distal end or portion of the flex tubes **306** may be fixedly coupled to the elongate instrument. In some variations, a proximal end or portion of the flex tubes may also be fixedly coupled to the elongate instrument **300** as in a passively controlled configuration of the flex tubes **306**.

For example, in a passively controlled configuration, the flex tubes **306** may passively slide along the interior of the operational tubes as the elongate instrument or catheter **300** is navigated through the anatomy, articulated or steered. As will be discussed in more detail, the slidable interface between the flex tubes **306** and the operational tubes **304** together with buffer loops of the flex tubes in the control unit substantially decouple the flex tubes **306** from the elongate instrument or catheter **300**. Because of the decoupled configuration of these two structures, articulation forces supported by the flex tubes may be decoupled from at least a portion of the catheter body or structure **300**. As a result of decoupling the flex tubes **306** from at least a portion the catheter body or structure, articulation forces applied to articulate or steer the distal portion of the elongate instrument or catheter **300** may not be transmitted through or along the body of the elongate instrument from the distal portion to the proximal portion of the elongate instrument, for example. Consequently, as described in this example, articulation forces may be prevented or minimized from compressing the proximal portion of the elongate instrument or catheter body; such compression if allowed to occur, may affect the stiffness or bending stiffness of the proximal portion of the catheter. In addition, this decoupling of the articulation forces for the elongate member allows that changes in the shape or length of the elongate member as it is navigated through the anatomy may not have any impact or minimal impact on the articulation performance of the distal section of the elongate instrument. As will be also discussed in more detail, in some embodiments, the flex tubes **306** may also be utilized as support or reinforcing structures to vary or change the stiffness and/or bend radius of at least a portion of the catheter. In particular, the flex tubes **306** may be very effective support or reinforcing structures when they are compressed and stiffened. In other words, an elongate instrument **300** or a section of the elongate instrument without any flex tubes **306** may be substantially flexible. With the introduction of one or more flex tubes **306** into the body of the elongate instrument or a section of the elongate instrument, the elongate instrument or the section of the elongate instrument with the flex tubes **306** may become less flexible; even though the flex tubes **306** are flexible in bending, they have axial stiffness. Several axially stiff members spread throughout the cross section of a catheter may add significant bending stiffness to the catheter. When the flex tubes **306** are compressed, such as using pull wires to apply a compressible force or load to the flex tubes, for example, they may become substantially more stiff laterally, such that the stiffened structures may affect or alter the stiffness and/or bend radius of at least a portion of the catheter where the flex tubes **306** are located. Accordingly, the flex tubes **306** may be utilized to vary or change the stiffness and/or bend radius of a portion or certain portion of the catheter by changing the positioning or placement of the flex tubes **306** in the elongate instrument **300**. For example, the flex tubes **306** may be moved from one portion of the elongate instrument or catheter to another portion of the catheter. The portion from which where the flex tubes **306** were moved may become substantially more flexible or pliable without the flex tubes **306**. Whereas, the portion to which where the flex tubes **306** were moved to may become substantially more stiff or less flexible or pliable. Consequently, the changes of stiffness along various portions of the elongate instrument or catheter may substantially affect the bend radius of at least a portion of the elongate instrument as pull wires are operated to articulate or steer the elongate instrument.

Referring back to the structural make up of the steerable instrument **300** as illustrated in FIG. **33**A, the flex tubes **306** may be made from a coil of wire, a stack of rings, or a tube with spirally cut features. As may be appreciated by one of ordinary skilled in the art, a substantially stiff tube may become less stiff or more flexible or more pliable as a spiral cut or spirally cut feature is imparted onto a substantially stiff tube. The tube may be made from a of a high durometer plastic such as Peek™ or stainless steel or other suitable material. One of the features of the flex tube **306** is that it may provide structural support to the elongate instrument (e.g., axial and lateral support) as well as being substantially flexible (e.g., able to bend in various directions and orientations). In some embodiments, the flex tubes **306** may be constructed from one continuous coil of wire, e.g., coil tube. In other embodiments, each flex tube **306** may include a plurality of coils that are axially aligned in series. In some other embodiment, the flex tube **306** may be constructed from a stack of rings, e.g., ring tube. For a ring tube, the rings may be stacked, grouped, or maintained together in any suitable manner. In some of the embodiments, the rings may be stacked, grouped, or maintained together by a substantially flexible sleeve, sheath, membrane, or covering. The coil of wire or rings may be made from a polymer material or metallic material. For example, a coil wire or rings may be made from stainless steel, Nitinol, etc. The coil wire may be made from a round stock or a flat stock or a stock having any cross-section or profile. Similarly, the rings of the ring tube may be made from a round stock or a flat stock or a stock having any cross-section or profile. In accordance with some embodiments, the flex tubes **306** may be generally constructed from a substantially tightly wound coil of wire or a stack of rings.

Still referring to FIG. **33**A, the support tubes **310** may be made of any suitable polymer material, bio-compatible polymer material, or metallic material (e.g., polyimide, stainless steel, Nitinol, etc.). The inner layer or inner tube **312** may be made of any suitable polymer material or bio-compatible polymer material (e.g., nylon-12, Pebax®, Pellathane, Polycarbonate, etc.). In addition, the elongate instrument **300** may include a control ring **316** that may be secured near a distal portion of the elongate instrument **300**. In various embodiments, the proximal end or portion of one or more pull wires **314** may be operatively coupled to various mechanisms (e.g., gears, pulleys, etc.) of a control unit or splayer (such as the drivable instrument **182**) of the instrument assembly. The pull wire **314** may be a metallic wire, cable or thread, or it may be a polymeric wire, cable or thread. The pull wire **314** may also be made of natural or organic materials or fibers. The pull wire **314** may be any type of suitable wire, cable or thread capable of supporting various kinds of loads without deformation, significant deformation, or breakage. The distal end or portion of one or more pull wires **314** may be anchored or mounted to the control ring **316**, such that operation of the pull wires **314** by the control unit or splayer may apply force or tension to the control ring **316** which may steer or articulate (e.g., up, down, pitch, yaw, or any direction in-between) certain section or portion (e.g., distal section) of the elongate instrument **300**. In other embodiments, no control ring may be used, instead the distal portion of the pull wires may be attached directly to a section or portion of the elongate instrument **300** where it may be steered, articulated, or bent. The wires may be crimped, soldered, welded or interlocked in any suitable manner to a specific location on a bending section or portion of the elongate instrument **300**. The control ring **316** or the attachment point(s) may be located at any location, section, portion, or region along the length of the elongate instrument **300**. Operation of the pull wires **314** may steer or articulate any of the location, section, portion, or region of the elongate instrument **300**, which may in effect provide or define various bend radii for the articulated portion of the elongate instrument **300**. In addition, in some embodiments there may be more than one control ring **316** mounted or installed to the elongate instrument **300** or more than one control wire attachment control locations, sections, or portions for controlling, steering, or articulating more than one section or portion of the elongate instrument **300**. In some embodiments, the flexible and steerable elongate instrument **300** having more than one control rings **316** or more than one control sections may be steered, articulated, or deflected into various complex shapes or curvatures (e.g., "S" curved shapes or "J" curved shapes, etc.). For example, the steerable elongate instrument **300** may be steered, articulated, or deflected into various complex shapes or curvatures that may conform to various complex shapes or curvatures of internal pathways of a patient to reach a target tissue structure of an organ inside the patient.

In some embodiments, one or more portions of the flex tubes **306** may be incorporated or coupled to the wall of the catheter **300** and such incorporation or coupling may be used for multiple functional purposes. For example, the coupling of the flex tubes **306** to the elongate instrument **300** may be used to support articulation forces as the elongate instrument or catheter is steered or articulated. Also, in some embodiments, proximal portions of the flex tubes **306** may be slidable relative to the elongate instrument **300**. As one or more of the pull wires **314** are operated by the control unit to steer or articulate the elongate instrument **300**, the articulation or steering forces may be substantially transmitted along the body of the elongate instrument **300** from the portion (e.g., distal portion) of the elongate instrument **300** where the distal end or portion of the pull wires **314** may be anchored to the proximal portion of the elongate instrument **300**. Since the flex tubes **306** are incorporated or coupled to the wall of the elongate instrument **300** and the flex tubes **306** are substantially configured to support axial loading, the articulation or steering loads may be decoupled from the elongate instrument **300** at the point or location where the flex tubes **306** are incorporated or coupled to the wall of the elongate instrument **300**. Hence, the proximal portion of the elongate instrument may be substantially unaffected by the articulation or steering of the particular section or portion (e.g., distal section or portion) of the elongate instrument **300**. The proximal portion of the elongate instrument may remain substantially flexible and pliable even when a particular portion (e.g., distal portion) of the elongate instrument is being articulated or steered. The above feature allows tension to be applied to steer the distal section of the elongate instrument **300** while steering force is isolated from the proximal section of the elongate instrument **300** (and as a result, a bending stiffness of the proximal section of the elongate instrument **300** is not significantly affected). The above feature also allows tension to be applied to steer the distal section of the elongate instrument **300** without creating unwanted curvature at the proximal section of the elongate instrument **300**, and thus, a shape of the proximal section of the elongate instrument **300** is unaffected by the steering of the distal section. As such, an operator or surgeon may easily manipulate the elongate instrument **300** and urge it to conform, adopt, or match the various shape or curvatures of the internal pathways of a patient while the elongate instrument is being advanced and steered to reach various tissue structures or target sites inside a patient. In another example or application of the elongate instrument **300**, the flex tubes **306** may be used as a structural support member to the catheter **300**; in particular, when the flex tubes are stiffened by tensioning pull wires that may be attached to the flex tubes **306**. In such application, the flex tubes **306** may support not only axial forces or loads, but also lateral forces or loads. As such, the flex tubes may increase the lateral as well as bending stiffness of at least a portion or section of the elongate instrument **300**. In addition, the flex tubes **306** may also affect the bending radius of at least a portion or section of the elongate instrument **300** as the elongate instrument is steered, articulated, or manipulated.

In some embodiments, each flex tubes **306** may be located closer to a wall of the elongate instrument **300** than an axis (e.g., central axis) of the elongate instrument **300**. For example, in some variations, each flex tubes **306** may be located close to a wall of the elongate instrument **300**. This allows the elongate instrument **300** to have a central working lumen extending therethrough. In some cases, such central working lumen may have a cross sectional area that is at least 30% of the cross sectional area of the elongate instrument **300**. Also, in one or more of the embodiments described herein, each flex tube **306** may have a proximal tip that is proximal to a proximal tip of the tubular body of the elongate instrument **300**.

FIG. **33**B illustrates another cross-sectional view (View **1-1**) of a section or portion of a steerable elongate instrument or catheter **300**. As illustrated in FIG. **33**B, the components of the elongate instrument **300** may be contained within or between the outer layer of material or outer tube **302** and the inner layer of material or inner tube **312**. A primary, main, central, or working lumen **318** may be provided or defined by the inner layer of material or inner tube **312**. The main lumen or central lumen **318** may be used to pass surgical instruments from the proximal end to the distal end of the elongate instrument **300** for performing various minimally invasive surgical procedures. Many of the components of the elongate instrument **300**, e.g., operational tubes **304**, flexible tubes **306**, push tubes **308**, and support tubes **310**, are disposed within the minor, secondary, or peripheral lumens in the body structure of the elongate instrument, as illustrated in FIG. **33**A and FIG. **33**B. In some embodiments, one or more pull wires **314** may be disposed within lumens of the support tubes **310**, lumens of the flex tubes **306**, and lumens of the push tubes **308**. As illustrated in FIG. **33**A, the distal end or portion of the support tubes **310** may be secured or anchored near the distal portion of the elongate instrument **300** and the proximal end of the support tubes **310** may be slidably coupled to the distal end or portion of the flex tubes **306**. In one embodiment, the distal portion of the flex tubes **306** may be secured at respective anchor points or regions **320** of the elongate instrument **300**. Anchoring the flex tubes **306** to the elongate instrument **300** may provide the connections or couplings that allow force or load to be transferred from the flex tubes **306** to the elongate instrument **300** when force or load is applied to the flex tubes. For example, in some embodiments the flex tubes **306** may be actively controlled, that is one or more push tubes **308** or control members **308** may be configured to push against respective flex tubes **306**. The applied force from the push tubes or control members **308** may be transmitted by way of the anchoring points **320** through the flex tubes **306** to the elongated instrument **300**. In this way, at least a portion of the elongate instrument **300** may be steered or shaped by the push tubes or control members **308**. Similarly, articulation or steering forces or loads may be transferred or coupled at the anchor points **320** from one portion (e.g., distal portion) of the elongate instrument **300** to the flex tubes **306**, such that the flex tubes **306** may act as load bearing support elements for another portion (e.g., proximal portion) of the elongate instrument **300** where the force or load may be decoupled or not transmitted. In other words, the anchor points **320** may function as coupling points from one portion (e.g., distal portion) of the elongate instrument **300** to the flex tubes **306** where force or load may be transferred from one portion (e.g., distal portion) of the elongate instrument to the flex tubes. Similarly, the anchor points **320** may also function as decoupling points between one portion (e.g., distal portion) of the elongate instrument **300** to another portion (e.g., proximal portion) of the elongate instrument **300** where force or load may be decoupled or not transferred from one portion (e.g., distal portion) of the elongate instrument to another portion (e.g., proximal portion) of the elongate instrument.

In some embodiments, the location of the anchor points **320** may be varied to control the radius of curvature of a bending section of the elongate instrument **300** as the elongate instrument is articulated or steered. In some embodiments, the flex tubes **306** may be anchored at substantially the same points or regions of the elongated instrument **300**. In some embodiments, the flex tubes **306** may be anchored at substantially different points or regions of the elongate instrument **300** to affect the bend radius of various portions of the elongate instrument **300** and/or various directions of steering or bending. The flex tubes **306** may be secured to the elongate instrument **300** in any suitable manner. In some embodiments, the distal portion of the flex tubes **306** may be fused with the material of the outer layer or outer tube **302**, such as by thermal fusion. Similarly, the material of the outer layer or outer tube **302** may be fused to the flex tubes **306**. For example, the flex tubes **306** may be fused to the outer layer or outer tube **302** at various places where it is not covered by the operational tubes **304**, as illustrated in FIG. **33**A. In some embodiments, the elongate instrument may be configured with displacement control of the flex members **306**. That is, a flex tube **306** may not be fixedly coupled to the elongate instrument, instead it may be displaced along the length of the elongate instrument **300**. Once the flex tube **306** is displaced to a desired location, the distal portion of the flex tube **306** may be secured or coupled to the elongate instrument **300** by a deployable and retractable anchor. The displacement of proximal portion of the flex tube **306** may be controlled by the push tube or control member **308**. The deployable anchor may be deployed to couple the flex tube **306** to a particular anchor point at a particular location on the elongate instrument. The anchor may also be retracted such that the flex tube **306** may be disengaged or separated from the elongate instrument **300** such that it may be displaced to a different location along the elongate instrument **300**.

As illustrated in FIG. **34**A, an elongate instrument **300** with passively controlled flex members **300** may be similarly configured as the elongate instrument structure illustrated in FIG. **33**A with the exception that the proximal portion of the flex members **300** may be fixedly coupled to the body of the elongate instrument, the control unit or splayer (such as the drivable instrument **182**), or some other structural element or component. In some embodiments, the push tube or control member **308** may not be included as a component of the elongate instrument **300** for a passively controlled flex member. In the passively controlled configuration, the flex members **306** may include a service or buffer loop **320**, as more clearly illustrated in FIG. **34**B. The service loop or buffer loop **320** on the flex members **306** may provide the extra service length or buffer length needed to isolate the articulation loads as the elongate instrument **300** is pushed through the anatomy, articulated or steered.

As the elongate instrument is pushed through the anatomy, steered or articulated, the support tubes **310** in the distal section may slide along the flex tubes **306** as indicated by the arrows in FIG. **34**C. The support tubes **310** may provide a lumen or path for the pull wires **314** to connect to the distal section of the catheter. The support tubes **310** may also provide some amount of structural rigidity or support to the distal portion of the elongate instrument **300**. In some embodiments, the elongate instrument **300** may not include any support tubes **310**. In some embodiments, one or more flex tubes **306** may be extended further into the distal portion of the elongate instrument **300** to provide some structural rigidity or support to the distal portion of the elongate instrument. In some embodiments, the flex tubes **306** may be substantially more stiff or more rigid than the support tubes **310**, such that when one or more flex tubes **306** are used as support structures to reinforce the distal portion of the elongate instrument **300**, the distal portion of the elongate instrument may be substantially more stiff or more rigid than when it is supported by the support tubes **310**. In some embodiments, the flex tube **306** may provide substantially the same or similar stiffness or structural support as the support tubes **310**, such that there may not be any significant difference if the flex tubes **306** or support tubes **310** are used to provide structural support to the distal portion of the elongate instrument **300**. In some embodiments, the flex tubes **306** may be substantially more flexible than the support tubes **310**, such that the distal portion of the elongate instrument may be substantially more flexible or less rigid than when it is supported by the flex tubes **306**.

Referring back to FIG. **34**A, the flex tubes **306** may be slidably coupled to the operational tubes **304** while fixed at the distal end **320**. As the elongate instrument **300** is steered or articulated, or as the catheter is advanced through the natural curvature of the body lumens, the flex tubes **306** may slide along the operational tubes **304** as indicated by the arrows illustrated in FIG. **34**D. In one scenario, for example, the elongate instrument **300** may be steered by operating or applying tension to one of the pull wires (e.g., **314**A) through operation of one or more gears and/or pulleys in the control unit or splayer. The tension on one of the pull wires (e.g., **314**A) may cause the elongate instrument **300** to bend, as illustrated in FIG. **34**D. The inside edge or inside region of the bend may be contracted or foreshortened, while the outside edge or outside region of the bend may be lengthened or stretched. The bend of the elongate instrument as described may cause one of the flex tubes (e.g., **306**A) to slide "out" near the proximal portion of the elongate instrument **300** at the contracted or foreshorten edge or region. In this same example, another one of the flex tubes (e.g., **306**B) may slide "in" near the proximal portion of the elongate instrument **300** at the lengthened or stretched edge or region, as illustrated in FIG. **34**D. In order to accommodate the sliding of "in" and "out" of the flex tubes **306**, the flex tubes may include a service loop or buffer loop **320** to allow for these "in" and "out" displacements or movements of the flex tubes **306**. As discussed, the flex tubes **306** may be passively constrained or restrained. The flex tubes **306** may be constrained or restrained by being coupled to the elongate instrument **300**, the control unit, or splayer. In addition, the flex tubes **306** may be constrained or restrained by hard-stops, tethers, etc. In some embodiments, the operational tubes **304** may be configured or allowed to float or slide substantially freely relative to the outer layer or outer tube **302**. In some other embodiments, the operational tubes **304** may not be configured or allowed to float or slide substantially freely relative to the outer layer or outer tube **302**.

FIG. **35**A through FIG. **35**C illustrate the operation of a substantially flexible and steerable elongate instrument in accordance with one embodiment. FIG. **35**A illustrates an elongate instrument **300** of an instrument assembly in a substantially neutral state. In this example, the elongate instrument **300** includes an outer body **302**, two sets of support tubes (not shown), operational tubes **304**A, **304**B, flex tubes **306**A, **306**B, and pull wires **308**A, **308**B. Each set of support tubes, operational tubes **304**A, **304**B, flex tubes **306**A, **306**B, and pull wires **308**A and **308**B) may be substantially axially aligned, and the pull wires **308**A, **308**B may be coupled to a control ring (not shown) or mounting points that are located at the distal section or portion of the elongate instrument **300**. As illustrated in FIG. **35**A, in the neutral state the flex tubes **306**A, **306**B and pull wires **308**A, **308**B may extend out of the operational tubes **304**A, **304**B at about the same amount or distance. As the substantially flexible and steerable elongate instrument **300** is advanced into the anatomy and natural pathway (e.g., blood vessel, gastrointestinal tract, etc.) of a patient, it may take on the shape of the natural pathway, as illustrated in FIG. **35**B. In this example, the proximal section **338** of the elongate instrument may be bent at a curvature induced by the natural pathway (e.g., blood vessel, gastrointestinal tract, etc.), while the distal section **336** may remain relatively straight or in a substantially neutral state. Due to the bend at the proximal section **338**, the flex tube **306**A and pull wire **308**A may slide "out" of the operational tube **304**A near the inside edge or inside region of the bend as it may be contracted or foreshortened, as indicated by the arrow illustrated in FIG. **36**B. At the same time, due to the bend at the proximal section **338**, the flex tube **306**B and pull wire **308**B may slide "in" to the operational tube **304**B near the outside edge or outside region of the bend as it may be lengthened or stretched, as indicated by the arrow illustrated in FIG. **35**B. As may be appreciated, it may be advantageous to maintain the induced shape or curvature of the proximal section **338** of the elongate instrument **300** and at the same time articulate or steer the distal section **336** of the elongate instrument **300** to treat a target site or toward a different direction down the natural pathway.

In other embodiments of an elongate instrument where flex tube or similar control or support structure may not be used, operating or tensioning a pull wire on the outside edge of a bend may cause the elongate instrument to rotate or twist as the pull wire may tend to rotate the distal section of the elongate instrument until the pull wire is at the inside edge of the bend; this rotation or twist phenomenon or occurrence is known as curve alignment.

FIG. **36**C illustrates an embodiment of an elongate instrument or catheter **300** that does not have coil pipes in the wall of the catheter. When the proximal section of the catheter is curved (as it tracked through curved anatomy), and the catheter distal section is required to be articulated in a direction that is not aligned with the curvature in the shaft, a wire on the outside of the bend is pulled. A torsional load (T) is applied to shaft as tension increases on the pull-wire on the outside of the bend. This torsional load rotates the shaft until the wire being pulled is on the inside of the bend. This un-intentional rotation of the shaft causes instability of the catheter tip and prevents the doctor from being able to articulate the catheter tip in the direction shown. The phenomenon is known as curve alignment because the wire that is under tension is putting a compressive force on both the proximal and distal sections and so both the proximal and distal curvature will attempt to align in order to achieve lowest energy state.

Embodiments described herein may substantially eliminate this problem by providing support structures such as flex tubes that could prevent curve alignment and substantially prevent or eliminate unwanted rotation or twist of the catheter. In other words, the pull wires, flex tubes, and the distal anchor points of the pull wires at the control ring or the body of the elongate instrument may all be substantially aligned, such that operating or tensioning of the pull wires would allow the elongate instrument to bend in a substantially aligned or neutral configuration with the longitudinal axis of the pull wire and flex tube. In this configuration, there may not be any component or vector of force or load that could cause the elongate instrument to rotate or twist resulting in curve alignment as the elongate instrument is steered or bent.

The design presented in FIG. **36**D and with service loops on the proximal end of the coils as per FIG. **34**B substantially eliminates or prevents curve alignment and the catheter may be biased, steered, or articulated in specific planes, e.g., X-Plane, Y-Plane, Z-Plane, of articulation. By using flex tubes with service loops as support structures or "backbones" to the catheter shaft, the path length of the wire under tension does not change as the proximal shaft is curved. The flex tubes isolate the forces from the proximal section and therefore there is no tendancy to curve align the distal section with the proximal section and hence no rotation of the shaft. In FIG. **36**A, as a pull wire is operated (indicated by the arrow) to steer the elongate instrument, the flex tube supports the pull wire and prevent it from moving to the inside edge of the bend, which may produce a force vector that could cause the elongate instrument to twist or rotate. In this example, the operation of the pull wire causes the distal section of the elongate instrument to be steered or articulated in a substantially upward movement, e.g., the direction or vector of articulation is in the Y-Plane. Similarly, as illustrated in FIG. **36**B, as a pull wire is operated (indicated by the arrow) to steer the elongate instrument, the flex tube supports the pull wire, maintain its alignment to the longitudinal axis, and prevent it from moving to the inside edge of the bend, which may produce a force vector that could cause the elongate instrument to twist or rotate. In this example, the operation of the pull wire causes the distal section of the elongate instrument to be steered or articulated in a substantial sideway or rightward movement, e.g., the direction or vector of articulation is in the X-Plane.

It should be noted that the catheter **300** is not limited to the configuration described previously, and that the catheter **300** may have other configurations in other embodiments.

FIG. **37**A illustrates a catheter **412** in accordance with other embodiments. The catheter **412** has a distal end **430**, a proximal end **432** coupled to the drivable assembly **182**, and a body **434** extending between the distal end **430** and the proximal end **432**. In some embodiments, the proximal end **432** is fixedly secured to a hypotube that is in turn fixedly secured to the drivable assembly **182**. The catheter **412** has a distal section **436** that articulates in response to control by the drivable assembly **182** and based on commands received at the workstation **2** or the bedside control **402**.

FIG. **37**B illustrates portion of the catheter **412** in further detail. As shown in the figure, the distal section **436** of the catheter **412** includes a spine **440** defining a lumen **441** for accommodating an instrument, such as a guidewire. The spine **440** is configured to provide support for the catheter **412**, and specific bending pivot point for the catheter **412**. The spine **440** may be made from a coil, or a tube with cutout slots to provide flexibility for the spine **440**. As shown in the figure, the spine **440** extends partially into the proximal section **438** of the catheter **412**. Alternatively, the spine **440** may extend all the way to the proximal end **432** of the catheter **412**.

The catheter **412** also includes a plurality of coils **442** positioned radially relative to the spine **440**. The coils **442** may be used to implement the flex tubes **306** in some embodiments. The coils **442** are configured (e.g., sized and/or shaped) to house respective control wires that are attached at their distal ends to a control ring **444**, and at their proximal ends to the drivable assembly **182**. In other embodiments, the each tube **306** may not be implemented using the coil **442**, and may be implemented using other elongate elements, such as a continuous tube with a smooth continuous surface, a wire cage having a tubular configuration, etc.

In some embodiments, the control wire coils **442** change coil pitch from the distal section **436** to the proximal section

438. In particular, the coil loops of the coils **442** are more spaced apart at the distal section **436**, but the coil loops of the coils **448** are closer together at the proximal section **438**. Such configuration is advantageous in that it provides a more flexible distal section **436** so that the distal section **436** may be bent to a more tight curve. In one implementation, the coils **442** may have an open pitch while the coils **448** may have a closed pitch. In such cases, the coils **448** are wound tightly so that they are in a naturally compressed state. In such configuration, when the steering wires are pulled in tension, the shaft does not bend and the forces are transmitted to the proximal end of the catheter. Alternatively, both the coils **442**, **448** may have closed pitch. In some embodiments, each distal coil **442** and its corresponding proximal coil **448** may be parts of a same coil structure, wherein the distal portion of the coil structure is constructed to have coil loops that are more spaced apart than a proximal portion of the coil structure. In other embodiments, the distal coil **442** may be a separate component that is connected to the proximal coil **448** (e.g., via a weld, adhesive, etc.).

In some embodiments, the coil **442** is anchored to the distal section **436** (e.g., the distal end), while the coil **448** is slidable relative to the proximal section **438**. In other embodiments in which the coils **442**, **448** are parts of a same coil, the coil may be fixed to the catheter body at the transition between the proximal section **438** and the bendable distal section **436**. In some embodiments, the coil **442** is anchored to the distal section **436** by anchoring at least a lengthwise portion of a distal portion of the coil **442** to the distal section **436**. The lengthwise portion may be at least 10 mm in some embodiments, and more preferably, at least 20 mm, and even more preferably, at least 30 mm. In other embodiments, the lengthwise portion may be at least 5% of a combined length of the coils **442**, **448**, and more preferably at least 10%, and even more preferably at least 20% of the combined length of the coils **442**, **448**. In other embodiments in which the coils **442**, **448** are parts of a same coil, the lengthwise portion may be at least 5% of a total length of the coil, and more preferably at least 10%, and even more preferably at least 20% of the total length of the coil.

During use, the drivable assembly **182** may apply tension to one or more control wires to thereby cause a corresponding bending at the distal section **436** of the catheter **412**. Although two control wire coils **442** for housing two respective control wires are shown, in other embodiments, the catheter **412** may have only one coil **442** for housing one control wire, or more than two coils **442** (e.g., four coils **442**) for housing more than two control wires (e.g., four control wires). The control ring **444** is embedded within a soft tip **445**, which is configured to minimize injury to tissue as the catheter **412** is advanced within the patient.

In some embodiments, the catheter **412** further includes an outer jacket **446** surrounding the coils **442**. The outer jacket **446** is a low durometer material for providing flexibility for the articulating distal section **436**. In some embodiments, the outer jacket **446** may be made from 35D or 25D Pebax, or from 70A or 80A Polyurethane. In other embodiments, the outer jacket **446** may be made from other materials as long as the distal section **436** is sufficiently flexible for it to be articulated.

In some embodiments, the outer jacket material **442** extends partially into the space that is between the loops of the coil **442** (FIG. **37**C). Such configuration prevents the control wire from contacting the material of the outer jacket material **442**, thereby allowing the control wire to be more easily slide within the lumen of the coil **442**. In other embodiments, the outer jacket material **442** may not extend partially into the space that is between the loops of the coil **442**. Instead, the outer jacket material **442** may be touching only the outer side of the coil **442**. This may allow the coils **442** to move relative to the outer jacket **446**, thereby improving the flexibility of the distal section **436**. In further embodiments, the outer jacket material **442** may extend completely into the space that is between the loops of the coil **442** (FIG. **37**D).

The above configurations shown in FIGS. **37**C and **37**D may be accomplished through a manufacturing process. For example, during a manufacturing process, a mandrel may be placed inside the coils **442** to ensure that the lumens remain unobstructed while the jacket is being laminated. The mandrel is then removed post lamination to leave a lumen (through the expanded coil encased in plastic) that the smaller diameter steering wire can slide through freely with minimum friction. In some embodiments, by varying the size of the mandrel in the lumen, the amount of encapsulation of the coils **442** with the plastic can be varied. For example, a 0.01" mandrel inside a 0.014" internal diameter coil will lead to a 0.002" of plastic inserted in through the coils **448**. On the other hand, a 0.014" mandrel placed inside a 0.014" coil will ensure that no plastic encapsulates the inside surface of the coil **442**. Limiting the plastic that is inserted through the coils **442** can reduce the friction when the steering wire is pulled since the wire slides more freely on the coils than on the softer plastic, as discussed. Thus, the catheter designer can trade off friction in the control wire lumen with structural integrity of the coils **442** by varying the outer diameter of the mandrel used in the manufacturing process.

Also, in some embodiments, during the design of the catheter **412**, the pitch of the coil **442** and/or the size of the coil **442** may be selected to define an amount of maximum bending for the catheter **412**. As shown in FIG. **37**E, as the distal section **436** of the catheter **412** is being bent due to a tensioning of a control wire, the coil loops of the coil **442** that is housing the control wire will move closer to each other. As a result, the material **456** of the outer jacket **446** that is between the coil loops will undergo compression. By varying the pitch of the coil **442** during the design of the catheter **412**, the amount of material **456** between the loops that would undergo compression would vary. Generally, the more material **456** that is between the loops (i.e., more spaced apart loops), the more bending will be allowed for the catheter **412**, and vice versa. Also, in other embodiments in which there is no jacket material between the loops of the coil **442**, the same design principle may apply. In such cases, the maximum amount of bending for the catheter **412** may be achieved when the distal section **436** is bent so much that the coil loops of the coil **442** abuts against each other. When the coils **442** abut against each other, no further articulation will be possible. Any additional force on the control wire will be transmitted directly and fully to the compressed coils **442** rather than the spine or the plastic of the articulation section. This has the benefit of preventing over-articulation that may lead to potential spine fracture, plastic deformation of the spine, or damage to the distal jacket. Thus, during the design of the catheter **412**, the loops of the coil **442** may be spaced apart further if more bending is desired for the catheter **412**, or spaced closer if less bending is desired. For example, a coil made of 0.003" wire with a 0.009" pitch will allow articulation of the catheter **412** to a smaller radius than a coil with a 0.006" pitch, for example.

In some embodiments, by varying the pitch of the coils **442**, the bend shape at the distal section of the catheter **412** may be adjusted. A more closely-spaced section of coils (e.g., 0.006") on the proximal end will result in a larger minimum radius—i.e., that section will remain straighter than regions with a larger coil pitch (e.g., 0.009" pitch) on the distal end.

This technique may be used to get small bend radii at the very distal end of the catheter **412**, which can be used to reach small vessels with acute take off angles.

It should be noted that use of the coils **442** as control wire lumens in the articulating section has several additional advantages. The coils **442** have both low axial and bending stiffnesses. This lowers articulation forces since the lumens on the inside and outside of the bend will more easily contract and expand, respectively. The coils **442** also have relatively high radial strength, ensuring that they do not collapse and pinch the control wire, which would undesirably increase the wire forces. Also, the coil's **442** ability to expand and contract will decrease the resistance to bending, and will yield a more uniform bend when compared to traditional polyimide lumen constructions. In addition, the coil **442** will provide a load-bearing surface that will radially distribute the control wire load about the jacket. The use of coils **442** will also allow the jacket material to be melted around the coils **442** to thereby secure the coils **442**. This will eliminate the need to braid the coils **442** onto a component of the catheter **412**. The elimination of braid will in turn lower the resistance to bending (i.e., lowering the bending stiffness) because different layers may shift relative to each other with a lower force, and will also yield a lower articulation force for the catheter **412** and/or smaller bending radius for the catheter **412**. However, in other embodiments, the coil **442** may still be braided to a reinforcement layer, such as a wire mesh or a spine. Alternatively, bands of higher durometer (e.g. 72D) crosslinked Pebax may be used to support the expanded coils and fix them to the spine. Cross linked Pebax has improved mechanical properties and greater dimensional stability and physical toughness compared to regular Pebax and ensures the coils are adequately fixed to the spine.

Returning to FIG. **37**B, as the distal section **436** transitions to the proximal section **438**, the material of the outer jacket also changes. In particular, proximal to the outer jacket **446**, the catheter **412** includes another outer jacket **454** that is stiffer than the material of the distal outer jacket **446**. In some embodiments, the outer jacket **454** may be made from a 40D or 55D Pebax. In other embodiments, the outer jacket **454** may be made from other materials as long as they are stiffer than that of the distal outer jacket **446**. In further embodiments, the outer jacket **454** may be made from the same material as that for the outer jacket **446**. In such cases, the outer jacket **446**, **450** may be formed together. Thus, the designer may vary the position of the jacket transition relative to the transition in the coil pipe spacing to get a gradual change in stiffness and hence curvature between the proximal and distal sections. This reduces the likelihood of any kink points in the catheter.

As shown in the figure, the proximal section **438** of the catheter **412** includes the proximal control wire coils **448**. The proximal section **438** of the catheter **412** also includes an inner jacket **452** surrounding the coils **448**, and an outer jacket **454** surrounding the inner jacket **452**. In some embodiments, the inner and outer jackets **452**, **454** are made from different materials. In other embodiments, the inner and outer jackets **452**, **454** may be made from the same materials. Also, in other embodiments, the inner jacket **452** and/or the outer jacket **454** may be made from a material that is stiffer than the material for the outer jacket **446** at the distal section **436** and/or the outer jacket at the transition section. In further embodiments, the inner jacket **452** and/or the outer jacket **454** may be made from the same material as the outer jacket at the transition section. The embodiments having the outer jacket and the inner jacket allow the designer flexibility to vary the stiffness of the catheter as desired throughout the length of the catheter, while at the same time ensuring that the steering lumens are encapsulated, that no braid is exposed, and that the structural integrity of the shaft is maintained. In addition, in one or more of the embodiments described herein the proximal section **438** of the catheter **412** may optionally further include a braid surrounding the coils **448** (e.g., embedded within the way of the jacket **452** or jacket **454**) for strengthening and stiffening the proximal section **438**. The braid can be stainless steel flat wire or round wire. The braid angle and pic count can be optimized to give the required stiffness and flexibility. The braid may have a constant pattern throughout the proximal section, or there may be a transition in the braid to enable higher bending stiffness at the proximal end (compared to the distal end) and higher flexibility at the distal end (compared to the proximal end).

The sheath **414** will now be described. FIG. **38** illustrates the sheath **414** in accordance with some embodiments. The sheath **414** includes a bendable distal section **470**, a proximal section **471**, and a distal soft tip **472**. The distal section **470** that is more flexible than the proximal section **471**. During use, in response to control by the drivable assembly **184**, the distal section **470** will bend based on commands received at the workstation **2** or the bedside control **402**. In some embodiments, the proximal end **471** is fixedly secured to a hypotube that is in turn fixedly secured to the drivable assembly **184**.

As shown in FIGS. **39** and **40**, the sheath **414** may also include a spine **478** in the distal section defining a lumen **441** for accommodating an instrument, such as the catheter **412**. The spine **478** is configured to provide support for the sheath **414**, and specific bending pivot point for the sheath **414**. The spine **478** may be made from a coil, or a tube with cutout slots to provide flexibility for the spine **478**.

As shown in FIGS. **38** and **39**, the sheath **414** may also include a plurality of coils **474** positioned radially relative to the spine **478**. The coils **474** are configured (e.g., sized and/or shaped) to house respective control wires **475** that are attached at their distal ends to the tip **472**, and at their proximal ends to the drivable assembly **184**. During use, the drivable assembly **184** may apply tension to one or more control wires **475** to thereby cause a corresponding bending at the distal section **470** of the sheath **414**. Although four control wire coils **474** for housing four respective control wires are shown, in other embodiments, the sheath **414** may have less than four coils **474** and control wires **475**, or more than four coils **474** and control wires **475**.

In the illustrated embodiments, the sheath **414** further includes an outer jacket **476** surrounding the coils **474**. The outer jacket **476** is a low durometer material for providing flexibility for the articulating distal section **470**. In some embodiments, the outer jacket **476** may be made from 35D or 55D Pebax, or from 70A or 80A Polyurethane. In other embodiments, the outer jacket **476** may be made from other materials as long as the distal section **470** is sufficiently flexible for it to be articulated.

In the illustrated embodiments, the control wire coils **474** have an open pitch so that the loops of the coils **474** are spaced apart. Such configuration is advantageous in that it provides a more flexible distal section **470** so that the distal section **470** may be bent to a more tight curve. In one implementation, the distal portion of the coil **474** may have an open pitch while the proximal portion of the coil **474** may have a closed pitch. In such cases, the proximal portion of the coil **474** are wound tightly so that they are in a naturally compressed state. In such configuration, when the steering wires are pulled in tension, the shaft does not bend and the forces are transmitted to the proximal end of the sheath. Alternatively, the entire length of the coil **474** may have a closed pitch. In some embodiments, each coil **474** may extend all the way to the proximal end of the sheath **414**. In other embodiments, each coil **474** may transition to another coil with a closer loop spacing at the proximal section **471**, as similarly discussed with reference to the catheter **412**. In such cases, each distal coil **474** and its corresponding proximal coil may be parts of a same coil structure, wherein the distal portion of the coil structure is constructed to have coil loops that are more spaced apart than a proximal portion of the coil structure. In other embodiments, the distal coil **474** may be a separate component that is connected to the proximal coil (e.g., via a weld, adhesive, etc.).

In the illustrated embodiments, the distal portion of the coil **474** is anchored to the distal section (e.g., the distal end) of the sheath, while the proximal portion of the coil **474** is slidable relative to the proximal section of the sheath. In other embodiments, the coil **474** may be fixed to the sheath body at the transition between the proximal section and the bendable distal section.

In some embodiments, the outer jacket material **476** extends partially into the space that is between the loops of the coil **474** (as similarly discussed with reference to FIG. **37**C). Such configuration prevents the control wire **475** from contacting the material of the outer jacket material **476**, thereby allowing the control wire **475** to be more easily slide within the lumen of the coil **474**. In other embodiments, the outer jacket material **476** may not extend partially into the space that is between the loops of the coil **474**. Instead, the outer jacket material **476** may be touching only the outer side of the coil **474**. This may allow the coils **474** to move relative to the outer jacket **476**, thereby improving the flexibility of the distal section **470**. In further embodiments, the outer jacket material **476** may extend completely into the space that is between the loops of the coil **474** (as similarly discussed with reference to FIG. **37**D).

Also, in some embodiments, the pitch of the coil **474** and/or the size of the coil **474** may be selected to define an amount of maximum bending for the sheath **414**. As similarly discussed with reference to FIG. **37**E, as the distal section **470** of the sheath **414** is being bent due to a tensioning of a control wire, the loops of the coil **474** that is housing the control wire **475** will move closer to each other. As a result, the material of the outer jacket **476** that is between the coil loops will undergo compression. By varying the pitch of the coil **474** during the design of the sheath **414**, the amount of material between the loops that would undergo compression would vary. Generally, the more the material that is between the loops (i.e., more spaced apart loops), the more bending will be allowed for the sheath **414**, and vice versa. Also, in other embodiments in which there is no jacket material between the loops of the coil **474**, the same design principle may apply. In such cases, the maximum amount of bending for the sheath **414** may be achieved when the distal section **470** is bent so much that the coil loops of the coil **474** abuts against each other. Thus, during the design of the sheath **414**, the coil loops of the coil **474** may be spaced apart further if more bending is desired for the sheath **414**, or spaced closer if less bending is desired.

In the above embodiments, the coils **474** are surrounded by the outer jacket **476**, which functions to contain the coils **474** during use. In other embodiments, the sheath **414** may further include a braided layer **480** for reinforcing the structure of the sheath **414** (FIGS. **41** and **42**). In such cases, the coils **474** for housing the control wires **475** may be coupled to the braided layer. As shown in FIG. **42**, in some embodiments, the coils **474** may be coupled to the outer surface of the braided layer **480**, e.g., by wrapping part of the coils **474** around the braided layer **480**, by attaching them using adhesive, etc. In other embodiments, the coils **474** may be coupled to the inner surface of the braided layer **480** (FIG. **41**), e.g., by wrapping part of the coils **474** around the braided layer **480**, by attaching them using adhesive, etc. In one approach, the coils **474** are braided by looping around the coil at the section closest to the sheath body, so that the braid will not tent over the coil. This braiding method eliminates the potential for the braid to apply loads on the control wires. This braiding approach will also minimize the coils natural tendency to peel away from the sheath **414** when high articulation forces are used, or when the jacket is made from a material with low durometer.

As shown in FIG. **43**, in some embodiments, different sections along the length of the sheath **414** may have different configurations to achieve different stiffnesses. In the implementation shown, the sheath **414** includes a HDPE liner and two layers of stainless steel braid that extend all the way from the drivable assembly **184** to the distal end of the sheath **414**. The liner is a coextrusion of HDPE and plexar. The plexar is a tie layer and its purpose is to ensure that the liner is properly bonded to the outer jacket extrusions. The distal 27 mm of the braid on the top layer is 100 ppi while the remainder of the top braid is at 40 ppi. In other embodiments, the pic count of the braid may also change on the bottom layer. This allows for increased stiffness in the proximal section and increased flexibility at the distal section (e.g., the distal 27 mm length) without increasing the risk of kinking. The length of the 100 ppi section can be longer or shorter than 27 mm to a give longer or shorter distal segment. In addition, the outer jacket transitions from a relatively stiff 70D pebax (not shown) in the tracking section of the sheath to 55D Pebax for a 10 cm region at the transition to the bending section. This is then followed by approximately 25 mm of articulation region. This change in durometer of the outer jacket, combined with the change in braid coverage contribute to a sharp change in stiffness in the articulation region which enables a 90° or more articulation angle to be achieved.

As shown in FIG. **44**, the spine **478** and/or the braided layer **480** of the sheath **414** may have a square cross section in at least a section along the length of the sheath **414**. In such cases, the coils **474** and the control wires **475** may be placed next to the straight side of the square cross section. Such configuration allows more of the jacket material **476** to be surrounding the coils **474**, thereby reducing the risk that the coils **474** may cut through the jacket material **476** due to the tensioning of the control wires **475**.

It should be noted that use of the coils **474** as control wire lumens in the articulating section has several additional advantages. The coils **474** have both low axial and bending stiffnesses. This lowers articulation forces since the lumens on the inside and outside of the bend will more easily contract and expand, respectively. The coils **474** also have relatively high radial strength, ensuring that they do not collapse and pinch the control wire, which would undesirably increase the wire forces. Also, the coil's **474** ability to expand and contract will decrease the resistance to bending, and will yield a more uniform bend when compared to traditional polyimide lumen constructions. In addition, the coil **474** will provide a load-bearing surface that will radially distribute the control wire load about the jacket. The use of coils **474** will also allow the jacket material to be melted around the coils **474** to thereby secure the coils **474**. This will eliminate the need to braid the coils **474** onto a component of the sheath **414**. The elimination of braid will in turn lower the resistance to bending (i.e., lowering the bending stiffness) because different layers may shift relative to each other with a lower force, and will also yield a lower articulation force for the sheath **414** and/or smaller bending radius for the sheath **414**. However, in other embodiments, if the anchor strength of the coil **474** is desired to be improved, the coil **474** may still be braided to a reinforcement layer, such as a wire mesh or a spine.

In one or more of the embodiments of the catheter **412** and the sheath **414** described herein, the catheter **412** and/or the sheath **414** may not include any spine structure and/or any braided layer. This may have the benefit of further improving the flexibility of the catheter **412** and/or the sheath **414** at the articulating section.

To illustrate the benefits of the configurations of the catheter **412** and the sheath **414** described herein, a method of reaching a target region using a catheter and a sheath will be described. In particular, FIG. **45** shows a catheter C inserted in the right common femoral artery. The tip of the sheath C is positioned in the right common iliac artery and the catheter C is extended from the tip of the sheath to reach the iliac bifurcation. Next, the steerable distal section of the catheter C is pulled back and articulated towards the left common iliac artery and the guidewire G is advanced out from the tip of the catheter C. The guidewire G is then advanced towards the left external iliac artery. Once the guidewire G is advanced far enough to provide sufficient support for the catheter C, the control wires in the catheter C can be slacked (by removing tension in the control wires). This lowers the distal stiffness, and allows the catheter C to track more easily over the guidewire. If the catheter C is advanced distally at this point, the catheter C may sometimes follow the guidewire G over the bifurcation and into the left common iliac artery (as illustrated by the dashed path). However, in some patients with tight iliac bifurcations, the catheter C may not follow the guidewire G, but instead will prolapse up into the aorta. The force applied at the point of insertion is in the direction of the aorta, and so the catheter C may tend to move in that direction.

By providing the sheath **414** with the features described herein, the sheath **414** can be advanced forward and the distal articulation section of the sheath **414** can be articulated towards the left common iliac (FIG. **46**) to support the leader. Once the sheath **414** is in this position, the shape of the sheath **414** can be locked by maintaining tension on the control wires. Next, the catheter **412** can be advanced, and the catheter **412** will deflect off the sheath **414** (rather than the artery wall), and can be advanced into the left common iliac (instead of prolapsing up into the aorta). As the catheter **412** is advanced through the deflected sheath **414**, the tension on the control wire(s) of the catheter **412** is removed, and the distal steering section of the catheter **412** is allowed to straighten or to conform to whatever shape imposed by the shape of the sheath **414**. As such, the shaft of the catheter **412** will follow through the articulated sheath **414**. The articulated sheath **414** functions like a pre-shaped or curved lumen for the catheter **412** to be advanced therethrough. Since the sheath **414** provides the support to direct the path of the catheter **412** over the bifurcation, no tension is required on the control wires of the catheter **412** to track over the bifurcation in this example. Therefore, even if the iliac bifurcation is at a very tight angle (in some cases up to 180°), the catheter **412** can still be advanced through the sheath lumen without placing any stress or shearing forces on the wall of the artery. The insertion force may increase on the catheter **412** as the bifurcation angle gets tighter, but the loads are being applied to the inside of the sheath **414**, and not to the patient anatomy. In some embodiments, the steerable sheath **414** may be adjusted to ensure that its position and/or shape can be maintained on the sheath distal section as the catheter **412** is advanced through the sheath **414**. For example, the instrument driver assembly **408** may compensate for the increased load by pulling more on the control wires or slightly withdraw the sheath **414** to ensure that the sheath **414** will not damage the artery wall. In some embodiments, during the procedure, the inner surface of the sheath **414** and/or the outer surface of the catheter **412** may optionally be coated with a lubricous coating.

As illustrated in the above example, the sheath **414** or leader may be articulated to have a tight bend during a procedure. Embodiments of the sheath **414** and leader described herein allow this to happen. In particular, the control wire coils **474** in the sheath **414** or leader isolate the articulation loads from the shaft, thereby allowing the sheath **414** or leader shaft to be manufactured from low durometer flexible materials. As a result, the articulation loads are resolved via the control wire coils **474** which have a relatively high axial stiffness and low bending stiffness. These control wire coils **474** allow the distal section of the sheath **414** or leader to be articulated to a small radius, and at the same time, the proximal section of the sheath **414** or leader can be maintained very flexible.

FIGS. **47** and **48** illustrate another method for advancing the sheath **414** and the catheter **412** over the iliac bifurcation. In this technique, the catheter **412** is positioned with its distal articulation section traversing the iliac bifurcation and it is locked in this position. Embodiments of the catheter **412** described herein allows the catheter **412** to reach tight angle that may be encountered during the procedure. Next, the sheath **414** is advanced over the catheter **412**, and the catheter **412** acts as a rail held in a fixed shape for the sheath **414** to glide over. As the sheath **414** is advanced further, sections with higher bending stiffness on the sheath **414** will pass over the articulated section of the catheter **412**, putting an increase load on the catheter **412**. The increase in load on the catheter **412** may tend to straighten the catheter **412**. Embodiments of the catheter **412** described herein allows the catheter **412** to maintain its bent shape by tightening the control wire(s), which has the effect of stiffening the catheter **412**. In some embodiments, the robotic system is configured to detect the increased load on the control wires (due to the placement of the sheath **414** over the catheter **412**) to be detected. The operator, or the robotic system, can then apply an equal counteracting load on all the control wires of the catheter **412** to ensure that its bent shape is maintained while the sheath **414** is advanced over the iliac bifurcation.

The doctor can continue to advance the catheter **412** through the articulated sheath **414**. He can continue to steer the tip of the catheter **412** to access the required points of interest in the patient's left leg (FIG. **48**). In particular, FIG. **48** shows how the catheter **412** can be articulated to reach the left internal iliac artery. This articulation of the catheter **412** is carried out simultaneously with the continued insertion of the catheter **412**. This requires the shaft of the catheter **412** to remain flexible at all times even when high articulation loads are being applied to bend the articulation section. Embodiments of the catheter **412** described herein allow this to happen. In particular, the control wire coils **442** in the catheter **412** isolate the articulation loads from the catheter shaft, thereby allowing the catheter **412** shaft to be manufactured from low durometer flexible materials. As a result, the articulation loads are resolved via the control wire coils **442** which have a relatively high axial stiffness and low bending stiffness. These control wire coils **442** allow the distal section of the catheter **412** to be very bendable, and at the same time, the proximal section of the catheter **412** can be maintained very flexible. Also, in some cases, the design of the catheter **412** described herein obviates the need to maintain the proximal section of the catheter **412** to be straight during use, which may be the case with some existing catheters. In particular, the embodiments of the catheter **412** described herein allow high degrees of bendability at the distal section of the catheter **412** while also allowing a flexible proximal and middle segments. This achieves consistent bending at the distal section of the catheter **412** which is independent of the shape of the proximal section of the catheter **412**.

As illustrated in the above embodiments, the catheter design is advantageous over existing catheters. In steerable catheters, when the steering wire in the wall of a catheter is pulled, a pull force F_p is applied through the centre line of the pullwire. A reaction force is then generated by the catheter body to resist this pull force. This reaction force F_r is typically applied uniformly around the body or circumference of the catheter. The summation of the reaction force F_R is applied on the center line of the catheter. The offset between the pull force and the reaction force generates a moment at the tip of the catheter. This moment is what causes the catheter to bend. In some catheters in which the entire length of a catheter is built with a uniform bending stiffness, then the entire catheter would bend uniformly. Such configuration does not result in bending of the distal section only. Some other existing catheters have attempted to address this issue by substantially increasing the bending stiffness in the proximal section of the catheter and leaving the distal section of the catheter very flexible. In this situation, when the wire is pulled, the proximal section bends only slightly (because it is stiffer) and the majority of the displacement occurs at the softer distal section. While this solution (of stiffening the proximal end) is applicable for some catheters, it will not work where the proximal section of the catheter is required to remain very flexible to traverse through tortuous anatomy such as in vascular applications. Each of the steering wires are offset from the center line of the catheter and so when the wires are tensioned to steer the catheter tip, the resulting compressive forces on a flexible catheter shaft cause unwanted stiffening of the catheter shaft, especially in the proximal section, which is undesirable. Other steerable catheters and endoscopes attempt to overcome this problem by moving the pull wires to the center of the catheter at the proximal section. By moving the pullwires to the centerline of the catheter, unwanted deflection in the shaft is eliminated, and stiffening of the catheter at the proximal section is somewhat reduced. However, this solution will not work in situation in which an open lumen down the center of the catheter is required.

Embodiments of the catheter design described herein addresses all of the above problems and is specifically applicable for catheters that require (1) significant articulation performance at the distal end, (2) a very flexible catheter shaft (especially at the proximal section), and (3) an open lumen through the middle of the catheter to deliver therapy or other devices. The design involves putting an axially stiff tube (e.g., coil) into the wall of the shaft and using this tube to isolate the steering loads from the catheter shaft. As a steering wire is pulled, the reaction load F_r is applied uniformly by the wall of the coil, and the summation of the reaction force is now applied through the center of the coil pipe and not the center of the catheter. The proximal section of the coil may be tightly wound to take the reaction force. Because of this, the pull force F_P of the steering wire and the reaction force F_R by the coil are collinear and there is no moment generated in the proximal section of the catheter. The coil in the distal section remains loosely wound so it does not take any axial load and applies no reaction force. Therefore, the reaction force at the distal section of the catheter will continue to be applied about the centerline (or cross sectional centroid) of the catheter. This ensures that there is a moment generated at the distal section of the catheter and so the tip continues to bend when a pull force is applied to the wire. The additional benefit of placing an axially stiff member in the wall of the catheter is that it shifts the neutral axis from the catheter cross sectional centroid to the cross sectional centroid of the coil. There is significant benefit for articulation consistency when the pullwire is on the neutral axis. Therefore, this design biases the neutral axis of the catheter to make it collinear with a pullwire in the wall at the proximal section. The above design allows the catheter shaft (at least the proximal section) to be made from very flexible material. This ensures that the proximal section of the catheter can freely bend independently to fit through tortuous anatomy, regardless of how the distal section is steered.

In the above procedures, the catheter **412** and the sheath **414** work together in a telescoping motion to minimize stress on the wall of the arteries. Although the procedure is described with reference to traversing a tight iliac bifurcation, in other embodiments, the similar technique may be used to access other locations in the patient. For example, in other embodiments, similar technique may be used to access carotid arteries with tight take off angles from the aortic arch.

In some embodiments, after the catheter **412** has been driven to a desired location, a valve (shown in FIG. **49**) on the proximal end of the catheter **412** or sheath may be tightened, and the doctor may then inject contrast through the catheter **412** or sheath to perform a selective angiogram of the region of interest. The passive hemostatic seal on the proximal end of the sheath is supported by a Touhy Borst fitting on the illustrated embodiment to ensure that it can maintain the high injection pressures. Once the contrast injection is complete, the Touhy Borst fitting is loosened and the passive valve continues to ensure hemostasis against the surface of the guidewire. FIGS. **50**A-**50**C show the Touhy Borst valve in further details. In particular, FIGS. **50**A and **50**B illustrate front and back perspective views of a valve assembly **484** which is configured to be coupled at its distal end to a support tube **483** and configured to receive the guide wire **482** co-axially at its proximal end. FIG. **50**C illustrates an exploded view of the valve assembly **484** including a tube nut **485**, a flush joint **486**, a passive valve **487**, a cap **488**, a valve body **489**, a Touhy Borst body **490**, a Touhy Borst seal **491**, and a Touhy Borst nut **492**. The passive valve **487** has a slit that is configured to hold hemostasis when nothing is inserted therethrough. The cap **488** has a hole that is configured to hold hemostasis when a wire or a catheter is inserted through it. The support tube **483** which can be coupled to the guide catheter (not shown) at its distal end can be inserted into the flush joint **486** and locked into position by tightening the tube nut **485**. The guide wire **482** can be inserted through the proximal end of the Touhy Borst nut **492** and through the central lumen of the remainder of the valve assembly **484** eventually being fed co-axially into the support tube **483** and ultimately the guide catheter. Alternatively, the Touhy Borst can be tightened onto the leader catheter to facilitate contrast injection through the sheath. The Touhy Borst nut **492** is tightened to compress the Touhy Borst seal **491** into a sealed or completely sealed position. During operation, fluid may be introduced through a flush port **493** on the flush joint **486**. The passive valve **487** acts as a one-way valve which allows the guide wire **482** to be inserted towards the distal end of the valve assembly **484** but prevents fluid from flowing towards the proximal end of the valve assembly. Thus the pressurized fluid is forced to flow through the support tube **483**, and the flush of contrast is delivered to the region of the vasculature. The Touhy Borst seal **491** may be used as a secondary seal in the case where high pressure fluid is introduced which cannot be contained by the passive seal **487**. In one or more of the embodiments described herein, the valve may be adjustable such that it will seal automatically as the contrast injection pressure is being applied. Also, in other embodiments, instead of using a Touhy Borst valve, other types of valve may be used.

Also, in some embodiments, once the guide wire **482** has been positioned distal of a stenosis in an artery, the catheter **412** can be withdrawn completely from the sheath **414**, leaving the wire **482** and the sheath **414** in place. Next, a therapy of choice can be selected, and delivered over the wire **482** to the site of interest. By means of non-limiting examples, the therapy can range from balloon expandable stents, self expanding covered and/or uncovered stent, as well as a range of artherectomy devices that can traverse over the wire **482**. As the therapy is being delivered, the user continues to have the ability to steer the distal end of the sheath **414** to help ensure that the therapy can be delivered to the desired location. For example, as the therapy is being delivered through the anatomy, the sheath **414** may tend to move away from the target location. The doctor can adjust tension on the control wires of the sheath **414** as required to compensate for this movement and ensure that the therapy will reach the required location.

III. Bedside Configuration

FIGS. **51**A-**51**F illustrate another robotic surgical system **400** in accordance with other embodiments. The robotic surgical system **400** is similar to the embodiment described previously, except that it further has both a bed-side control **402** and a bed-side display (not shown). The bed-side control **402** is configured to provide some or all of the functions that the workstation can provide, so that the physician can perform most robotic catheter control tasks at either the workstation or the bed-side.

The system **400** also includes a setup mount (setup joint) **404** that is similar to that discussed previously. However, in the illustrated embodiments, the setup mount **404** is mounted to the patient support **22** via a rail system **406**. The rail system **406** allows the setup mount **404** (and therefore, the instrument driver assembly **16**) to translate along the length of the patient support **22**. In some embodiments, the rail system **406** includes a motorized rail **407**, that can be actuated to drive movement of the setup mount **404**. In other embodiments, other mechanisms may be used, including but not limited to a lead screw, a ball screw, linear motor, belt, and/or cable drive, etc. The movement of the setup mount **404** along the rail may be caused by entering a command at the workstation, or at the bedside control **402**. In other embodiments, the setup mount **404** may be allowed to move by actuating a button at the setup mount **404**, thereby releasing the setup mount **404** from a locked position against the rail system **406**. The setup mount **404** can then be translated manually along the axis of the patient support **22**. When the setup mount **404** has reached a desired position, the button may be released to lock the setup mount **404** at the desired position. Setup mount/joint has been described in U.S. Pat. No. 7,789,874, filed on Jul. 1, 2005, the entire disclosure of which is expressly incorporated by reference herein. Alternatively, the movement of the setup mount **404** along the rail may be controlled using the workstation **2** and/or the bedside control **402**. In one or more of the embodiments described herein, any of the controls, including release lever/button, may be implemented at any location, such as at the bedside control **402**, at the workstation **2**, on the side opposite from the side at which the bedside control **402** is located, etc. Also, in some embodiments, two release levers/buttons may be provided, with one located on the doctor's side (e.g., at the bedside control **402**), and another one on the back side for ease of service and safety.

Also, in other embodiments, the rail system **406** may be configured to tilt the setup mount **404** (as illustrated by the arrows in FIG. **51**G) in response to command entered at the workstation **2** and/or the bedside control **402**. In some cases, the tilting range of the angle can be up to 20° or higher. Such configuration allows the insertion trajectory of the catheter **412** and/or the sheath **414** to be tilted (e.g., relative to the bed). In other embodiments, the rail system **406** may be configured to move in other directions in other degrees of freedom. For example, in other embodiments, the rail system **406** may move up and down to adjust the height, and/or laterally towards either side of the bed. In further embodiments, the rail system **406** may roll (e.g., tilted about its longitudinal axis). Also, in one or more of the embodiments described herein, there may be an angular motion or indexed tilt of the rail about any axis to better align with the catheter insertion, and compensate for any sagging of the catheter or an anti-buckling device (which is described herein). In further embodiments, the rail system **406** may have a 10 degree angle (or other angles) incline. In the embodiments shown in FIG. **51**A, the rail shark fin (the triangular plate on one side of the bed) is configured to allow adjustment of the rail incline in 5 degree increments up to 20 degrees.

The robotic system **400** also includes an instrument driver assembly **408**. The instrument driver assembly **408** includes a catheter drivable assembly **182** for positioning a catheter **412**, and a sheath drivable assembly **184** for positioning a sheath **414** that is placed coaxially around the catheter **412**. The instrument driver assembly **408** is similar to that discussed previously. In the illustrated embodiments, the sheath drivable assembly **184** is moveable relative to the catheter drivable assembly **182**. Each of the drivers **82**, **84** has four drivable elements for moving the catheter **412**, and the sheath **414**, respectively, in different directions. In other embodiments, the number of drivable elements in each of the drivers **82**, **84** may be less than four or more than four. The instrument driver assembly **408** also includes two anti-buckling devices **500***a*, **500***b* for preventing the buckling of the catheter **412**, and the buckling of the sheath **414** during use. The anti-buckling devices will be described in further detail below. The instrument driver assembly **408** further includes a guide wire manipulator **410** for positioning a guidewire (not shown) that may be placed within a lumen of the catheter **412**.

IV. Driving Modes and Clinical Applications

The instrument driver assembly **408** may be configured to move the sheath **414** distally or proximally, move the catheter **412** distally or proximally, and to move the guidewire distally or proximally. In some cases, the movement of the sheath **414** may be relative to the catheter **412**, while the catheter **412** remains stationary. In other cases, the movement of the catheter **412** may be relative to the sheath **414** while the sheath **414** remains stationary. Also, in other cases, the sheath **414** and the catheter **412** may be moved together as a unit. The guidewire may be moved relative to the sheath **414** and/or the catheter **412**. Alternatively, the guidewire may be moved together with the sheath **414** and/or the catheter **412**.

In some embodiments, each of the workstation **2** and the bedside control **402** is configured to provide some or all of the following commanded motions (driving modes) for allowing the physician to choose. In some embodiments, each of the driving modes may have a corresponding button at the workstation **2** and/or the bedside control **402**.

Guidewire Insert—When this button/command is selected, the guide wire manipulator **410** inserts the guidewire at a constant velocity.

Guidewire Roll—When this button/command is selected, the guide wire manipulator **410** rolls the guidewire at a constant angular velocity

Guidewire Size—When the size or gauge of the guidewire is inputted into through the user interface, the system will automatically alter roll and insert actuation at the proximal end of the guidewire accordingly to achieve desired commanded results. In one implementation, when a user inputs the guidewire size, the system automatically changes its kinematic model for driving that guidewire. So if the user commands a guidewire to move to a certain position, the system will calculate, based on the kinematic model, roll and insert commands, which may be different for different guidewire sizes (e.g., guidewires with different diameters). By inputting the guidewire size, the system knows which kinematic model to use to perform the calculation. Such feature is beneficial because different sized guidewires behave differently.

Leader/Sheath Select—When this button/command is selected, it allows the user to select which device (e.g., catheter **412**, sheath **414**, guidewire, or any combination of the foregoing) is active.

Leader/Sheath Insert/Retract—When this button/command is selected, the instrument driver assembly **408** inserts or retracts the catheter **412**/sheath **414** while holding the guidewire and any non-active device fixed relative to the patient. When this motion causes the protruding section of the catheter **412** to approach zero (due to insertion of the sheath **414** or retraction of the catheter **412**), the system automatically relaxes the catheter **412** as part of the motion.

Leader/Sheath Bend—When this button/command is selected, the instrument driver assembly **408** bends the articulating portion of the catheter **412**/sheath **414** within its currently commanded articulation plane.

Leader/Sheath Roll—When this button/command is selected, the instrument driver assembly **408** uses the pullwires to "sweep" the articulation plane of the device (catheter **412** and/or sheath **414**) around in a circle through bending action of the device. Thus, this mode of operation does not result in a true "roll" of the device in that the shaft of the device does not roll. In other embodiments, the shaft of the device may be configured to rotate to result in a true roll. Thus, as used in this specification, the term "roll" may refer to an artificial roll created by seeping a bent section, or may refer to a true roll created by rotating the device.

Leader/Sheath Relax—When this button/command is selected, the instrument driver assembly **408** gradually releases tension off of the pullwires on the catheter **412**/sheath **414**. If in free space, this results in the device returning to a straight configuration. If constrained in an anatomy, this results in relaxing the device such that it can most easily conform to the anatomy.

Guide Wire Lock—When this button/command is selected, the guide wire position is locked to the leader position. As the leader is articulated or inserted, the guide wire moves with the leader as one unit.

System Advance/Retract—When this button/command is selected, the instrument driver assembly **408** advances/retracts the catheter **412** and sheath **414** together as one unit. The guidewire is controlled to remain fixed relative to the patient.

Autoretract—When this button/command is selected, the instrument driver assembly **408** starts by relaxing and retracting the catheter **412** into the sheath **414**, and then continues by relaxing and retracting the sheath **414** with the catheter **412** inside it. The guidewire is controlled to remain fixed relative to the patient.

Initialize Catheter—When this button/command is selected, the system confirms that the catheter **412** and/or the sheath **414** has been properly installed on the instrument driver assembly **408**, and initiates pretensioning. Pretensioning is a process used to find offsets for each pullwire to account for manufacturing tolerances and the initial shape of the shaft of the catheter **412** and/or the sheath **414**.

Leader/Sheath Re-calibration—When this button/command is selected, the instrument driver assembly **408** re-pretensions the catheter **412** and/or the sheath **414** in its current position. This gives the system the opportunity to find new pretension offsets for each pullwire and can improve catheter driving in situations where the proximal shaft of the catheter **412** has been placed into a significant bend such as after crossing the illiac bifurcation. It is activated by holding a relax button down for several seconds which ensures that the device is fully de-articulated. Alternatively the re-calibration may be activated without holding down the relax button to de-articulate the device.

Leader Relax Remove—When this button/command is selected, the instrument driver assembly **408** initiates a catheter removal sequence where the catheter **412** is fully retracted into the sheath **414**, all tension is released from the pullwires, and the splayer shafts (at the drivable assembly **182** and/or drivable assembly **184**) are driven back to their original install positions so that the catheter **412** can be reinstalled at a later time.

Leader Yank Remove—When this button/command is selected, the instrument driver assembly **408** initiates a catheter removal sequence where the leader is removed manually.

Emergency Stop—When this button/command is selected, the instrument driver assembly **408** initiates a gradual (e.g., 3 second) relaxation of both the catheter **412** and the sheath **414**. The components (e.g., amplifier) for operating the catheter **412**, guidewire, or another device are placed into a "safe-idle" mode which guarantees that no power is available to the motors that drive these elements, thereby bringing them rapidly to a stop, and allowing them to be manually back-driven by the user. Upon release of the emergency stop button, the system ensures that the catheter **412** is still in its allowable workspace and then returns to a normal driving state.

Segment control: In some embodiments, the workstation **2** and/or the bedside control **402** allows a user to select individual segment(s) of a multi-segment catheters (such as the combination of the catheter **412** and the sheath **414**), and control each one. The advantage of controlling the catheter in this way is that it allows for many options of how to control the movement of the catheter, which may result in the most desirable catheter performance. To execute this method of catheter steering, the user selects a segment of the catheter to control. Each segment may be telescoping or non-telescoping. The user may then control the selected segment by bending and inserting it using the workstation **2** and/or the bedside control **402** to control the position of the end point of the catheter. Other segment(s) of the catheter will either maintain their previous position (if it is proximal of the selected section) or maintain its previous configuration with respect to the selected section (if it is distal of that section) (FIG. **52**A).

Follow mode: In some embodiments, the workstation **2** and/or the bedside control **402** allows the user to control any telescoping section while the more proximal section(s) follows behind automatically. This has the advantage of allowing the user to focus mostly on the movement of a section of interest while it remains supported proximally. To execute this method of catheter steering, the user first selects a telescoping section of the catheter to control. This section is then controlled using the workstation **2** and/or the bedside control

402 to prescribe a location of the endpoint of the segment. Any segment(s) distal of the section of interest will maintain their previous configuration with respect to that section. When the button on the workstation **2** or the bedside control **402** is released, any segment(s) proximal of the section of interest will follow the path of the selected section as closely as possible until a predefined amount of the selected section remains (FIG. **52**B). As an alternative to this driving mode, the segment(s) of the catheter which is proximal of the section of interest could follow along as that segment is moved instead of waiting for the button to be released. Furthermore, with either of these automatic follow options, the system may optionally be configured to re-pretension the sections that have been driven out and re-align the sections that are proximal of the driven section.

Follow mode may be desirable to use to bring the more proximal segments of the catheter towards the tip to provide additional support to the distal segment. In cases where there are three or more controllable sections of the catheter, there are several options for how to execute a "follow" command. Consider the example in FIG. **52**D where the distal segment has been driven out as shown in frame **1**. The "follow" command could be executed by articulating and/or inserting only the middle segment of the catheter as shown in frame **2**. The "follow" command could be executed by articulating and/or inserting only the most proximal segment of the catheter as shown in frame **3**. The "follow" command could also be executed by coordinating the articulation and/or insertion of multiple proximal segments of the catheter as shown in frame **4**. Combining the motion of multiple sections has several potential advantages. First, it increases the total degrees-of-freedom available to the algorithm that tries to fit the shape of the following section(s) to the existing shape of the segment being followed. Also, in comparison to following each segment sequentially, a multi-segment follow mode simplifies and/or speeds up the workflow. In addition, multi-segment increases the distance that can be followed compared to when only one proximal segment is used to follow the distal segment.

Mix-and-match mode: In some embodiments, the workstation **2** and/or the bedside control **402** allows the user to have the option of mixing and matching between articulating and inserting various sections of a catheter. For example, consider the illustration in FIG. **52**C, and assuming that the distal most section of the catheter is the "active" segment. If the user commands a motion of the tip of the catheter as indicated by the arrow in Frame **1**, there are several options available for how to achieve this command: (1) Articulate and extend the "active" segment, which is illustrated in frame **3** and is likely considered the normal or expected behavior; (2) Articulate the active distal most segment and insert one of the other proximal segments, as illustrated in frames **2** and **4**; (3) Articulate the active distal most segment and combine inserting motion of some or all of the segments, as illustrated in frame **5**.

There are multiple potential reasons why the user might want to choose some of these options. First, by "borrowing" insert motion from other segments, some of the segments could be constructed with fixed lengths. This reduces the need for segments to telescope inside of each other, and therefore reduces the overall wall thickness. It also reduces the number of insertion degrees-of-freedom needed. Also, by combining the insert motion from several segments, the effective insert range-of-motion for an individual segment can be maximized. In a constrained space such as the vasculature, the operator may likely be interested in "steering" the most distal section while having as much effective insertion range as possible. It would simplify and speed up the workflow to not have to stop and follow with the other segments.

Locking mode: In some embodiments, the workstation **2** and/or the bedside control **402** may be configured to allow any of the section (e.g., proximal section) of a catheter to be "locked" into a given shape. Some driving modes that may take advantage of such feature include: (1) Locking the proximal segment into its current shape after each motion of the proximal segment is executed. The proximal section would then unlock whenever it is given another follow motion command. These motion commands would be either direct driving of the most proximal section or following of the more distal sections. (2) Leave the proximal section flexible for insertion by hand, then lock the proximal section once the catheter is attached to the robotic system. The proximal section could then be unlocked again for further manual insertions, either by removing the catheter from the instrument driver assembly **408** or by releasing the brake on the setup joint **404**. For any of these options, the locking portion could be: (1) The proximal (actively) articulating segment, (2) some or all of the "body" of the catheter proximal of the actively articulating segments, or (3) both the proximal actively articulating segment and some portion of the non-articulating "body" of the catheter.

In other embodiments, the "follow" mode may be carried out using a robotic system that includes a flexible elongated member (e.g., a guidewire), a first member (e.g., the catheter **412**) disposed around the flexible elongated member, and a second member (e.g., the sheath **414**) disposed around the first member. The flexible elongated member may have a pre-formed (e.g., pre-bent) configuration. In some embodiments, the flexible elongated member may be positioned inside a body. Such may be accomplished using a drive mechanism that is configured to position (e.g., advance, retract, rotate, etc.) the flexible elongated member. In one example, the positioning of the flexible elongated member comprises advancing the flexible elongated member so that its distal end passes through an opening in the body.

Next, the first member is relaxed so that it has sufficient flexibility that will allow the first member to be guided by the flexible elongated member (that is relatively more rigid than the relaxed first member). In some embodiments, the relaxing of the first member may be accomplished by releasing tension in wires that are inside the first member, wherein the wires are configured to bend the first member or to maintain the first member in a bent configuration. After the first member is relaxed, the first member may then be advanced distally relative to the flexible elongated member. The flexible elongated member, while being flexible, has sufficient rigidity to guide the relaxed first member as the first member is advanced over it. The first member may be advanced until its distal end also passes through the opening in the body.

In some embodiments, the second member may also be relaxed so that it has sufficient flexibility that will allow the second member to be guided by the flexible elongated member (that is relatively more rigid than the relaxed second member), and/or by the first member. In some embodiments, the relaxing of the second member may be accomplished by releasing tension in wires that are inside the second member, wherein the wires are configured to bend the second member or to maintain the second member in a bent configuration. After the second member is relaxed, the second member may then be advanced distally relative to the flexible elongated member. The flexible elongated member, while being flexible, has sufficient rigidity to guide the relaxed second member as the second member is advanced over it. The second member may be advanced until its distal end also passes through the opening in the body. In other embodiments, instead of advancing the second member after the first member, both the first member and the second member may be advanced simultaneously (e.g., using a drive mechanism) so that they move together as a unit. In further embodiments, the acts of advancing the flexible elongated member, the first member, and the second member may be repeated until a distal end of the flexible elongated member, the first member, or the second member has passed through an opening in a body.

In the above embodiments, tension in pull wires in the second elongated member is released to make it more flexible than the first elongated member, and the second elongated member is then advanced over the first elongated member while allowing the first elongated member to guide the second elongated member. In other embodiments, the tension in the pull wires in the first elongated member may be released to make it more flexible than the second elongated member. In such cases, the more flexible first elongated member may then be advanced inside the more rigid second elongated member, thereby allowing the shape of the second elongated member to guide the advancement of the first elongated member. In either case, the more rigid elongated member may be locked into shape by maintaining the tension in the pull wires.

In some of the embodiments described herein, the flexible elongated member may be a guidewire, wherein the guidewire may have a circular cross section, or any of other cross-sectional shapes. Also, in other embodiments, the guidewire may have a tubular configuration. In further embodiments, the robotic system may further include a mechanism for controlling and/or maintaining the preformed configuration of the guidewire. In some embodiments, such mechanism may include one or more steering wires coupled to a distal end of the guidewire. In other embodiments, such mechanism may be the catheter **412**, the sheath **414**, or both. In particular, one or both of the catheter **412** and the sheath **414** may be stiffened (e.g., by applying tension to one or more wires inside the catheter **412** and/or the sheath **414**). The stiffened catheter **412** and/or the sheath **414** may then be used to provide support for the guidewire.

Also, in some of the embodiments described herein, any movement of the guidewire, the catheter **412**, and/or the sheath **414** may be accomplished robotically using a drive assembly. In some embodiments, the drive assembly is configured to receive a control signal from a processor, and actuate one or more driveable elements to move the guidewire, the catheter **412**, and/or the sheath **414**.

It should be noted that the driving modes for the system are not limited to the examples discussed, and that the system may provide other driving modes in other embodiments.

V. Clinical Applications

The different driving modes and/or different combinations of driving modes are advantageous because they allow a tubular member (catheter **412**, sheath **414**, or combination of both) to access any part of the vasculature. Thus, embodiments of the system described herein may have a wide variety of applications. In some embodiments, embodiments of the system described herein may be used to treat thoracic aneurysm, thoracoabdominal aortic aneurysm, abdominal aortic aneurysm, isolated common iliac aneurysm, visceral arteries aneurysm, or other types of aneurysms. In other embodiments, embodiments of the system described herein may be used to get across any occlusion inside a patient's body. In other embodiments, embodiments of the system described herein may be used to perform contralateral gait cannulation, fenestrated endograft cannulation (e.g., cannulation of an aortic branch), cannulation of internal iliac arteries, cannulation of superior mesenteric artery (SMA), cannulation of celiac, and cannulation of any vessel (artery or vein). In further embodiments, embodiments of the system described herein may be used to perform carotid artery stenting, wherein the tubular member may be controlled to navigate the aortic arch, which may involve complex arch anatomy. In still further embodiments, embodiments of the system described herein may be used to navigate complex iliac bifurcations.

In addition, in some embodiments, embodiments of the system described herein may be used to deliver a wide variety of devices within a patient's body, including but not limited to: stent (e.g., placing a stent in any part of a vasculature, such as the renal artery), balloon, vaso-occlusive coils, any device that may be delivered over a wire, an ultrasound device (e.g., for imaging and/or treatment), a laser, any energy delivery devices (e.g., RF electrode(s)), etc. In other embodiments, embodiments of the system described herein may be used to deliver any substance into a patient's body, including but not limited to contrast (e.g., for viewing under fluoroscope), drug, medication, blood, etc. In one implementation, after the catheter **412** (leader) is placed at a desired position inside the patient, the catheter **412** may be removed, leaving the sheath **414** and guidewire to provide a conduit for delivery of any device or substance.

In further embodiments, embodiments of the system described herein may be used to access renal artery for treating hypertension, to treat uterine artery fibroids, atherosclerosis, and any peripheral artery disease.

In still further embodiments, embodiments of the system described herein may be used to access any internal region of a patient that is not considered a part of the vasculature. For example, in some cases, embodiments of the system described herein may be used to access any part of a digestive system, including but not limited to the esophagus, liver, stomach, colon, urinary tract, etc. In other embodiments, embodiments of the system described herein may be used to access any part of a respiratory system, including but not limited to the bronchus, the lung, etc.

In some embodiments, embodiments of the system described herein may be used to treat a leg that is not getting enough blood. In such cases, the tubular member may access the femoral artery percutaneously, and is steered to the aorta iliac bifurcation, and to the left iliac. Alternatively, the tubular member may be used to access the right iliac. In one implementation, to access the right iliac, the drive assembly may be mounted to the opposite side of the bed (i.e., opposite from the side where the drive assembly is mounted in FIG. **1**). In other embodiments, instead of accessing the inside of the patient through the leg, the system may access the inside of the patient through the arm (e.g., for accessing the heart).

In any of the clinical applications mentioned herein, the telescopic configuration of the catheter **412** and the sheath **414** (and optionally the guidewire **482**) may be used to get past any curved passage way in the body, like that similarly discussed with reference to FIGS. **45-48**. For example, in any of the clinical applications mentioned above, the guidewire **482** may be advanced first, and then followed by the catheter **412**, and then the sheath **414**, in order to advance the catheter **412** and the sheath **414** distally past a curved (e.g., a tight curved) passage way. In other embodiments, the catheter **412** may be advanced first, and then followed by the sheath **414**, in order to advance the catheter **412** and the sheath **414** distally past a curved (e.g., a tight curved) passage way. In still further embodiments, the guidewire **482** may be advanced first, and then followed by the catheter **412** the sheath **414** (i.e., simultaneously), in order to advance the catheter **412** and the sheath **414** distally past a curved (e.g., a tight curved) passage way.

VI. Anti-Buckling Feature

FIG. **53**A illustrates an implementation of the instrument driver **408** that includes the first and second drivable assemblies **182**, **184** removeably coupled to a base. The second drivable assembly **184** is slidable relative to the first drivable assembly **182**. In the illustrated embodiments, the drivable assembly **184** is configured to control movement of a sheath, and the drivable assembly **182** is configured to control movement of a catheter member that is inserted into the sheath. During use, the drivable assembly **184** may be controlled to move the sheath distally towards the patient, or proximally. Also, the drivable assembly **182** may be controlled to move the catheter member towards the patient, or proximally. In another mode of operation, the drivable assembly **184** may maintain the sheath to be stationary while the drivable assembly **182** moves the catheter member distally or proximally relative to the sheath. In still another mode of operation, the drivable assembly **182** may maintain the catheter member to be stationary while the drivable assembly **184** moves the sheath distally or proximally relative to the catheter member. In another mode of operation, the drivers **182**, **184** may cooperate with each other to move the catheter member and the sheath together (either distally or proximally), so that the catheter member with the sheath can translate as a unit.

As discussed, during an operation, the instrument driver assembly **408** may be configured to advance an elongate member (e.g., the sheath, the catheter member, or combination of both, any of which may be considered a medical device) distally towards the patient. In some embodiments, the elongate member may be constructed to be very flexible. In such cases, to prevent the elongate member from buckling while the elongate member is advanced towards the patient, an anti-buckling device may be coupled to the instrument driver assembly **408** to support the elongate member.

FIG. **53**B illustrates an anti-buckling device **500***a* that is configured to detachably couple to the drivable assembly **184** and the drivable assembly **182** during use. As shown in FIG. **53**B, the anti-buckling device **500***a* has a first end **504** for detachably coupling to the drivable assembly **182**, and a second end **506** for detachably coupling to the drivable assembly **184**. During use, the anti-buckling device **500***a* is placed around the elongate member **490** (which may be a catheter member, or another elongate medical device). The anti-buckling device **500***a* is then secured to the drivable assembly **182** at the first end **504**, and to the drivable assembly **184** at the second end **506**. The anti-buckling device **500***a* provides support along the length of the elongate member **490** between the drivers **82**, **84**, so that as the elongate member **490** is pushed towards the patient (resulting in the elongate member **490** being compressed), the catheter elongate **490** is prevented from buckling.

FIG. **53**C illustrates another variation of an anti-buckling device **500***b* that is configured to detachably couple to the drivable assembly **184** and a stabilizer **502** during use. As shown in FIG. **53**C, the anti-buckling device **500***b* has a first end **504** for detachably coupling to the drivable assembly **184**, and a second end **506** for detachably coupling to the stabilizer **502**. During use, the stabilizer **502** is attached to a patient's skin, and the anti-buckling device **500***b* is placed around the elongate member **490**. The elongate member **490** may be a sheath, a catheter member, a combination of both the sheath and the catheter member, or another elongate medical device. The distal end of the elongate member **490** is then inserted into the patient through the stabilizer **502**. The anti-buckling device **500***b* is secured to the drivable assembly **184** at the first end **504**, and to the stabilizer **502** at the second end **506**. The anti-buckling device **500***b* provides support along the length of the elongate member **490** between the stabilizer **502** and the drivable assembly **184**, so that as the elongate member **490** is pushed towards the patient (resulting in the elongate member **490** being compressed), the elongate member **490** is prevented from buckling.

FIGS. **53**D and **53**E illustrate the anti-buckling device **500***a* in further detail. The anti-buckling device **500***a* includes a first coupler **508** at the first end **504**, a second coupler **509** at the second end **506**, and a plurality of support members **510**, **512**, **514** coupled between the couplers **508**, **509**. The first coupler **508** has a slot **530** configured (e.g., shaped and/or sized) to detachably mate with an anchor element **532** at the drivable assembly **182** (FIG. **53**H). The second coupler **509** has a slot **534** for receiving a protrusion **537** at the drivable assembly **184**, and an opening **536** for receiving a shaft **538** at the drivable assembly **184** (FIG. **53**I). The second coupler **509** may be detachably coupled to the drivable assembly **184** by placing the second coupler **509** over the shaft **538**, while allowing the protrusion **537** to pass the initial entry point at the coupler **509**. The coupler **509** is then rotated to lock the protrusion **537** within the slot **534**. In other embodiments, the coupler **509** may have different configurations. For example, in other embodiments, the coupler **509** may include an active valve connector hub that is configured to detachably couple to an active valve release hub (FIG. **53**M). This configuration allows a user to connect the connector hub to the active valve, and rotate it in order to open or close the active valve as desired.

Returning to FIG. **53**D, the support members **510** are on one side of the anti-buckling device **500***a*, the support members **512** are on the opposite side of the anti-buckling device **500***a*, and the support members **514** are located in the middle between the first and second sets of support members **510**, **512**. In the illustrated embodiments, support members **510***m* **512** create the scissor mechanism. The support members **514** create an additional set of linkages that is offset from the support members **510**, **512**. The purpose of the support members **514** is to hold the eyelets **540** in line. The elongate member held between two eyelets **540** will have much greater buckling resistance if the eyelets **540** are prevented from being rotated. In other embodiments, the number of support members **510**, **512**, **514** may be different from that shown in the figure. In particular, on one side of the anti-buckling device **500***a*, the support members **510***a*, **510***b* are rotatably coupled to the coupler **509** via joint **524**, and support members **510***u*, **510***v* are rotatably coupled to the coupler **508** via joint **526**. The rest of the support members **510***c*-**510***t* are coupled together via joints **528** between the first and second ends **504**, **506** in a scissor-like configuration. In other embodiments, the support members **514** are optional, and the anti-buckling device does not include the support members **514**.

As shown in FIG. **53**E, on the other side of the anti-buckling device **500***a*, the support members **512***a*, **512***b* are rotatably coupled to the coupler **509** via joint **524**, and support members **512***u*, **512***v* are rotatably coupled to the coupler **508** via joint **526**. The rest of the support members **512***c*-**512***t* are coupled together via joints **528** between the first and second ends **504**, **506** in a scissor-like configuration.

It should be noted that providing two sets of support members **510**, **512** are advantageous in that they collectively provide sufficient stiffness for the anti-buckling device **500***a* in the Y-direction so that the anti-buckling device **500***a* will not sag or deflect significantly in the Y-direction between the supports at ends **506**, **506**. In other embodiments, the support members **510** may be made sufficiently stiff, and the joints coupling the various components of the anti-buckling device **500***a* may be configured to have a tight tolerance. In such cases, the anti-buckling device **500***a* may not require the second set of support members **512**.

In the illustrated embodiments, the anti-buckling device **500***a* also includes a plurality of connectors **516** that connects the support members **510**, **512**, **514**. Each connector **516** includes a first joint **518** for rotatably coupling to two of the support members **510**, a second joint **520** for rotatably coupling to two of the support members **512**, and a third joint **522** for rotatably coupling to two of the support members **514**.

As shown in FIG. **53**K, the anti-buckling device **500***a* also includes a plurality of holders **540** coupled between the first and second sets of support members **510**, **512** at the respective joints **528**. Each holder **540** has an opening **542** for accommodating the elongate member **490**, a first joint **544** for rotatably coupling to one of the support members **514**, and a second joint **546** for rotatably coupling to another one of the support members **514**. The support members **514** together with the holders **540** are configured to support the elongate member **490** as the elongate member **490** is being inserted into the patient. In particular, as the anti-buckling device **500***a* is being extended (FIG. **52**L) (e.g., by moving the ends **504**, **506** further away from each other) or collapsed (FIG. **53**D) (e.g., by moving the ends **504**, **506** closer towards each other), the support members **514** are configured to move the holders **540** along the longitudinal axis of the elongate member **490** relative to the elongate member **490** so that the holders **540** are spaced substantially evenly or equally along the axis of the elongate member **490**. In some embodiments, the holders **540** are considered to be spaced substantially evenly or equally when their spacing does not vary by more than 20%. The support members **514** also maintain all of the holders **540** in the same orientation relative to each other as the anti-buckling device **500***a* is being extended or collapsed.

In one or more of the embodiments described herein, the support members **510** (or members **512**, or members **14**) at one end (e.g., end **504** or **506**) of the anti-buckling device **500** may optionally have mating gears (FIG. **53**J). This ensures that the support members **510**/**512**/**514** on either side of the longitudinal axis **541** along the length of the anti-buckling device **500** will rotate by the same amount relative to the axis **541**. This feature is also advantageous because it ensures that the holders **540** will be oriented so that the axis of the opening **542** for each of the holders **540** is substantially parallel to the longitudinal axis **541** of the anti-buckling device **500**.

As shown in the illustrated embodiments, the anti-buckling device **500***a* provides a plurality of supports at the locations of the holders **540** that are evenly spaced along the length of the elongate member **490** regardless of how much the elongate member **490** is inserted into the patient (i.e., regardless of the distance between the first and second ends **504**, **506**). The plurality of supports shortens the buckling length of the elongate member **490**, thereby significantly improving the buckling strength of the elongate member **490**. It should be noted that the plurality of supports will prevent the elongate member **490** from buckling in a direction within the X-Z plane because the anti-buckling device **500***a* is very stiff in X-Z plane. Also, since the anti-buckling device **500***a* is relatively stiffer than the elongate member **490** in the Y-direction, the anti-buckling device **500***a* will also provide supports for the catheter member in all directions within the Y-Z plane to prevent the elongate member **490** from buckling in a direction that is within the Y-Z plane.

In other embodiments, to increase the rigidity of the anti-buckling device, the support members **510**, **512**, **514** may be implemented using a combination of a composite beam and a plastic beam (FIG. **53**L). As shown in FIG. **53**L, the composite beam may be formed from two stainless steel members that are spaced apart from each other with two stainless steel spacers therebetween. The plastic beam may be a PEEK beam. The composite beam and the plastic beam may be linked together to the connector **516** at one end via a hinge (e.g., rivet(s)).

The anti-buckling device **500***a* may be made from a variety of different materials. For example, in some embodiments, the support members **510**, **512**, **514** may be made from metal, alloys, plastics, polymers, etc. Also, in some embodiments, the connectors **516**, and the couplers **508**, **509** may be made from metal, alloys, plastics, polymers, etc. In addition, in one or more of the embodiments described herein, any moving parts in the anti-buckling device that contact each other may be made from the same material (e.g., stainless steel), or different materials (e.g., stainless steel for one, and PEEK for the other). Making two contacting parts that interact with each other with different respective materials is advantageous because it may allow the moving parts to move relatively to each other more easily without seizing. Furthermore, in one or more of the embodiments described herein, one or more components (e.g., support members **510**, **512**, **514**) of the anti-buckling device may be made from a light weight material, such as PEEK (plastic), to reduce the overall weight of the anti-buckling device. Also, in one or more of the embodiments described herein, any of the joints (e.g., joints **520**, joints **522**, or joints **528**) may be implemented using pins (e.g., dowel pins), rivets, or combination thereof. In one implementation, the support members **510**, **512**, **514** may be made from stainless steel and/or PEEK, the holders **540** may be made from PEEK, the rivets/pins may be made from stainless steel, the component housing the rivets/pins may be made from PEEK, and the end couplers **508**, **509** (and similarly, couplers **550**, **552** in the second anti-buckling device **500***b* shown in FIG. **53**F) may be made from PEEK/Ultem.

The second anti-buckling device **500***b* is illustrated in further detail in FIG. **53**F. The anti-buckling device **500***b* has the same configuration as the anti-buckling device **500***a*, except that it is used to prevent buckling between the drive assembly **184** and the insertion site or the patient. This insertion site may be at the left or right femoral artery or alternatively may be the left or right brachial artery, etc. Its proximal end **504** has a first coupler **550** for detachably coupling to the drivable assembly **184**, and its distal end **506** has a second coupler **552** for detachably coupling to the stabilizer **502** (FIG. **53**C). The first coupler **550** of the anti-buckling device **500***b* has the same configuration as the second coupler **509** of the anti-buckling device **500***a*, and is configured to detachably couple to a connector at the drivable assembly **184** (FIG. **53**G). As shown in FIG. **53**G, the second coupler **552** has an opening **554** for allowing the elongate member **490** to extend therethrough. The second coupler **552** also has a pair of protrusions **556** for inserting into a slot at the stabilizer **502**, and a wall **558** for allowing the stabilizer **502** to anchor thereto. The second coupler **552** may also be directly connected to the introducer sheath at the insertion site.

Refer now to FIG. **54**, the stabilizer **502** will now be described in further detail. The stabilizer **502** includes a base **560** with adhesive at its bottom side for attachment to a patient's skin, and a connector **562** for coupling with the coupler **552** of the anti-buckling device **500***b*. Alternatively, the base **560** or the coupler **552** may be attached to a bed or other support during use. In some embodiments, the base **560** may be a HDPE platform that includes a strain relief material underneath for providing transition from the rigid HDPE material to the patient skin. The base **560** may also include a butterfly peel-away liner (e.g., tear-resistant HDPE liner) that covers the adhesive material at the bottom side of the platform. During use, the liner may be peeled away to expose the adhesive at the bottom side of the base **560**. The stabilizer **502** also includes an opening **564** formed at the base **560** for allowing the elongate member **490** to reach the patient's skin. The interface mechanism **564** includes a pair of slots **566** for receiving the respective protrusions **556** at the coupler **552**, and a pair of moveable anchors **568** for anchoring against the wall **558** of the coupler **552**.

FIGS. **55**A and **55**B illustrate the stabilizer **502** in exploded view, particularly showing the components of the stabilizer **502**. The connector **562** includes a bottom piece **570** with the two slots **562**, a top piece **572**, and two rotatable anchoring components **574**, **576** located between the bottom piece **570** and the top piece **572**. A screw **580** is provided for extending through the top piece **572**, and the anchoring components **574**, **576**, to reach screw opening **578** at the bottom piece **572**, thereby coupling the various components together. The connector **562** also includes a spring **582** (in the form of an elastic plate, e.g., formed using a metal, alloy, or plastic) for biasing the anchoring components **574**, **576** so that their respective anchors **568** are urged towards each other. During use, when the coupler **552** is inserted into the slots **566**, the insertion force will push wall **558** of the coupler **552** towards the anchors **568**, thereby spreading the anchors **568**. When the coupler **552** is further inserted into the slots **566**, the wall **558** will pass the anchors **568**, thereby allowing the anchors **568** to close towards each other due to the biasing force provided by the spring element **582**. The anchoring components **574**, **576** also include respective levers **584**, **586** for allowing a user to move the anchors **568** away from each other. In particular, when the levers **584**, **586** are pressed towards each other, they bend the spring **582** against the curvilinear support **588** at the bottom piece **570**, thereby overcoming the biasing force that was urging the anchors **568** towards each other. This allows a user to remove the coupler **552** from the connector **562** at the stabilizer **502**.

As shown in FIG. **55**C, in some embodiments, the system may further include a lubricating system **680** coupled to the stabilizer **502**. The lubricating system **680** is configured to apply fluid (e.g., saline, gel) onto the exterior surface of the catheter **412** as the catheter **412** is being advanced through the lubricating system **680**. As shown in FIGS. **55**D-**55**F, the lubricating system **680** includes a base **684** and a cover **682** coupled to the base **684** via a joint **686**. The hinge **686** allows the cover **682** to be rotated relative to the base **684**, so that the system is always in contact with the catheter irrespective of the angle of entry of the catheter into the patient. As shown in FIG. **55**F, the lubricating system **680** also includes a slot **688** formed at the base **684**, which is configured to mate with the ring structure formed around the opening **554** at the coupler **552** (FIG. **53**G). The lubricating system **680** also includes an absorbent material **690** underneath the cover **682**, wherein the material **690** has a slot or cut-portion **692** for applying fluid to the catheter **412**. During use, the catheter **412** exiting from the opening **554** at the coupler **552** will go through the slot or cut-portion **692**, thereby contacting the absorbent material **690**. The absorbent material **690** will be sterile and will be soaked with saline by the user at the start of the procedure and then it automatically applies the fluid onto the surface of the catheter **412** as it passes therethrough. In some embodiments, the catheter **412** may be coated with a hydrophilic coating to reduce friction as they are pushed through the anatomy. In such cases, the lubricating system **680** may be used to hydrate the hydrophilic coating to activate it. As illustrated in the above embodiments, the lubricating system **680** provides a self lubricating or self hydration mechanism for robotically controlled catheter. This is advantageous because the doctor who is controlling the catheter remotely would be unable to manually wet the catheter with a wet gauze.

It should be noted that the anti-buckling device **500** is not limited to the above configuration, and that the anti-buckling device **500** may have other configurations in other embodiments. For example, in other embodiments, instead of having three sets of supports **510**, **512**, **514**, the anti-buckling device **500** may include only two sets of supports. FIG. **56** illustrates another anti-buckling device **500** in accordance with other embodiments. The anti-buckling device **500** is similar to the embodiments of FIGS. **52** and **53**, except that it has one set of support members **510** on one side of the anti-buckling device **500**, and another set of support members **514** next to the first set of support members **510** for maintaining the holders **540** in the same orientation relative to each other. In the embodiment of FIG. **56**, the anti-buckling device **500** does not include the set of support members **512** like that shown in FIG. **52**. Also, unlike the embodiments of FIGS. **52** and **53**, the embodiment of FIG. **56** includes support members **514** only on one side, wherein the support members **514** are coupled to the respective joints **544** on only one side of the holders **540**. In other embodiments, additional support members **514** may be provided on the opposite sides, in which case, the support members **514** will be coupled to the respective joints **546** at the holders **540**. The anti-buckling device **500** shown in FIG. **56** may have different connectors (not shown) at opposite ends, such as those shown in FIGS. **52** and **53**, for detachably coupling to different medical devices/components.

As shown in FIG. **56**, the support members **512** are relatively thicker than those in FIGS. **52** and **53**. Such configuration provides sufficient stiffness for the anti-buckling device **500** in the Y-direction while obviating the need for the third set of support members **512**, so that the anti-buckling device **500** will not sag or deflect significantly.

In the embodiment of FIG. **56**, the support members **514** together with the holders **540** are configured to support the elongate member **490** as the elongate member **490** is being inserted into the patient. In particular, as the anti-buckling device **500** is being extended (e.g., by moving the ends **504**, **506** further away from each other) or collapsed (e.g., by moving the ends **504**, **506** closer towards each other), the support members **514** are configured to move the holders **540** along the longitudinal axis of the elongate member **490** so that the holders **540** are spaced evenly along the axis of the elongate member **490**. The support members **514** also maintain all of the holders **540** in the same orientation relative to each other as the anti-buckling device **500** is being extended or collapsed.

As shown in the illustrated embodiments, the anti-buckling device **500** provides a plurality of supports at the locations of the holders **540** that are evenly spaced along the length of the catheter member **90** regardless of how much the elongate member **490** is inserted into the patient (i.e., regardless of the distance between the first and second ends **504**, **506**). The plurality of supports shortens the buckling length of the elongate member **490**, thereby significantly improving the buckling strength of the elongate member **490**. It should be noted that the plurality of supports will prevent the elongate member **490** from buckling in a direction within the X-Z plane because the anti-buckling device **500** is very stiff in X-Z plane. Also, since the anti-buckling device **500** is relatively stiffer than the elongate member **490** in the Y-direction, the anti-buckling device **500** will also provide supports for the elongate member **490** in the Y-direction to prevent the catheter member **90** from buckling in a direction that is within the Y-Z plane.

In any of the anti-buckling devices described herein, the buckle resistance increases as the unsupported length of the catheter gets shorter. The length of the catheter outside the patient gets shorter as the catheter is advanced further into the patient. Thus, as the catheter is being advanced into the patient, the unsupported length of the catheter becomes shorter, resulting in a higher buckling resistance provided to the catheter by the anti-buckling device. Therefore, the anti-buckling device provides a variable stiffness that allows the catheter's buckling capacity to increase as the catheter is being advanced into the patient. The further the catheter is advanced into the patient, the higher the insertion force is required to advance the catheter. In some embodiments, the buckle force of the anti-buckling device is always higher than the catheter insertion force.

In one or more of the embodiments of the anti-buckling device **500** described herein, the anti-buckling device **500** should not be limited to the planar configuration, and the anti-buckling device **500** may have a non-planar configuration. For example, as shown in FIG. **57**, the anti-buckling device **500** may have a non-planar configuration that is formed by orienting the support members **510** and the support members **514** in respective truss-configurations. FIG. **57** shows the anti-buckling device **500** in an extended configuration, and FIG. **58** shows the anti-buckling device **500** in a collapsed configuration. FIG. **59** shows a cross section of the anti-buckling device **500**, particularly showing the support members **510** forming a truss configuration, and the support members **514** forming another truss configuration. In particular, each support member **510** forms an angle **590** relative to the X-Z plane, and each support member **514** forms an angle **592** relative to the X-Z plane. In the illustrated embodiments, the anti-buckling device **500** does not include the second set of support members **512**. However, in other embodiments, the anti-buckling device **500** may optionally further include the second set of support members **512**. In such cases, the support members **512** will be coupled to the joints **528** at the holders **540**.

As shown in the illustrated embodiments of FIG. **57-59**, the anti-buckling device **500** provides a plurality of supports at the locations of the holders **540** that are evenly spaced along the length of the elongate member **490** regardless of how much the elongate member **490** is inserted into the patient (i.e., regardless of the distance between the first and second ends **504**, **506**). The plurality of supports shortens the buckling length of the elongate member **490**, thereby significantly improving the buckling strength of the elongate member **490**. It should be noted that the plurality of supports will prevent the elongate member **490** from buckling in a direction within the X-Z plane because the anti-buckling device **500** is very stiff in X-Z plane. Also, due to the truss configurations of the support members **510**, **514**, the anti-buckling device **500** is also very stiff in the Y-direction. Thus, the anti-buckling device **500** will also provide supports for the elongate member **490** in the Y-direction to prevent the elongate member **490** from buckling in a direction that is within the Y-Z plane.

The anti-buckling device **500** shown in FIG. **57** may have different connectors (not shown) at opposite ends, such as those shown in FIGS. **52** and **53**, for detachably coupling to different medical devices/components.

FIG. **60** illustrates another anti-buckling device **500** in accordance with other embodiments. The anti-buckling device **500** is similar to the embodiment shown in FIG. **57**, except that each support members **510** has a different shape, and that the anti-buckling device **500** also includes additional support members **512** on the opposite sides. Also, the support members **514** in the anti-buckling device **500** of FIG. **60** are in the form of tension wires. During use, the support members **514** keep the holders **542** all aligned in the same orientation relative to each other.

In one or more of the embodiments described herein, the anti-buckling device **500** may not include the set of support members **514** that link the holders **540** together. FIG. **61**A illustrates a variation of the anti-buckling device **500** that does not include any linkage members **514** for the holders **540**. In the illustrated embodiments, the holders **540** are free to rotate relative to each other. In such cases, the elongate member **490** may be made to have a sufficient bending stiffness so that the bending stiffness of the elongate member **490** will prevent each holder **540** from rotating too much relative to the longitudinal axis of the anti-buckling device **500**. In such cases, while the stiffness of the elongate member **490** is sufficient to rotatably guide the holders **540**, it may be insufficient to prevent buckling of the elongate member **490** (i.e., in the situation in which there is no anti-buckling mechanism). During use, the anti-buckling device **500** may have an extended configuration, like that shown in FIGS. **61**A and **61**C, or a collapsed configuration, like that shown in FIGS. **61**B and **61**D.

FIG. **62** illustrates another variation of the anti-buckling device **500** in accordance with other embodiments. The anti-buckling device **500** includes a plurality of support members **600**. Although only two support members **600** are shown, in other embodiments, the anti-buckling device **500** may include more than two support members **600**. Each support member **600** has a first portion **602** and a second portion **604** that are secured to each other at their respective ends. The first portion **602** has an opening **606** that is aligned with an opening **608** at the second portion **604**. The openings **606**, **608** allow the elongate member **490** to extend therethrough during use. Each of the first and second portions **602**, **604** has a curvilinear profile. In one implementation, each of the portions **602**, **604** may be formed by bending a plate to a desired profile, and then securing them relative to each other at their respective ends. In other embodiments, each of the portions **602**, **604** may not have a curvilinear profile, and may instead have a rectilinear profile (e.g., a U or C shape with straight portions).

In the illustrated embodiments, each of the support members **600** is elastic, and can be deformed during use. In particular, the portions **602**, **604** may be bent to vary the distance between the openings **606**, **608**. For example, during use, the drivable assembly **184** may be moved towards the stabilizer **502** to move the elongate member **490** distally. Accordingly, the anti-buckling device **500** of FIG. **62**, which is placed around the elongate member **490** during use, is compressed. The compression of the anti-buckling device **500** causes the portions **602**, **604** to bend towards each other, thereby shortening the unsupported length of the elongate member **490** between the supports at the respective openings **606**, **608**.

The configuration of the anti-buckling device **500** of FIG. **62** is advantageous in that it has significantly fewer components (compared to the embodiments of FIGS. **52** and **53**). Also, the anti-buckling device **500** of FIG. **62** does not require separate holders and associated linkage for maintaining the holders in the same orientation. Instead, the openings **606**, **608** at the portions **602**, **604** of each support member **600** will be aligned in the same orientation as the anti-buckling device **500** is extended or collapsed. Furthermore, because each of the openings **606**, **608** circumscribes completely around the elongate member **490** during use, each of the portions **602**, **604** provides support against the elongate member **490** to prevent the elongate member **490** from buckling in any radial direction during use.

In other embodiments, the support members **600** do not need to be oriented in the same direction. Instead, a first set of every other support members **600** may be orientated in a first direction, and a second set of every other support members **600** may be oriented in a second direction that is perpendicular to the first direction (FIG. **63**).

FIG. **64**A illustrates another anti-buckling device **500** in accordance with other embodiments. The anti-buckling device **500** has a first portion **620** and a second portion **622** that can be detachably coupled to the first portion **620** in a zipper-like manner along the length of the elongate member **490** during use. As shown in FIG. **64**B, the first portion **620** and the second portion **622** have respective C-shape cross sections, and collectively define a space **624** for housing the elongate member **490** during use. In other embodiments, each of the first portion **620** and the second portion **622** does not need to have a C-shape cross section, and may have other cross sectional shapes as long as they provide support for the elongate member **490** to prevent it from buckling. **620** and **622** do not necessarily need to have C-shaped cross sections, and may have other cross-sectional shapes in other embodiments. The design can be adjusted to add bending stiffness as shown in FIG. **64**C or **64**D.

During use, the portions **620**, **622** of the anti-buckling device **500** is placed around the elongate member **490** (FIG. **64**A). The distal end of the anti-buckling device **500** is then secured to the stabilizer **502** (e.g., using coupler **522** or another securing mechanism). The anti-buckling device **500** may further include supports **626**, **628** that are proximal relative to the distal end of the anti-buckling device **500**. The supports **626**, **628** are configured to hold the portions **620**, **622**, respectively, as they are un-zipped. The drivable assembly **184** may be advanced towards the stabilizer **502** to push the elongate member **490** distally, thereby shortening the length between the stabilizer **502** and the drivable assembly **184**. When this occurs, parts of the portions **620**, **622** at their proximal ends unzip and translate through the supports **626**, **628**. Alternatively, the drivable assembly **184** may be retracted proximally to move away from the stabilizer **502**, thereby increasing the length between the stabilizer **502** and the drivable assembly **184**. Accordingly, parts of the portions **602**, **622** will come together and zip against each other in increase the support portion for the elongate member **490**. Thus, the amount of anti-buckling support provided by the anti-buckling device **500** for the elongate member **490** automatically increases in response to an increase in the unsupported length of the elongate member **490**, and automatically decreases in response to a decrease in the unsupported length of the elongate member **490**.

In other embodiments, the anti-buckling device **500** of FIG. **64**A may be used to support other parts of the elongate member **490**. For example, in other embodiments, the anti-buckling device **500** may provide anti-buckling support for the elongate member **490** that spans between the drivable assembly **182** and the drivable assembly **184** (FIG. **53**A).

FIG. **65**A illustrates another anti-buckling device **500** in accordance with other embodiments. The anti-buckling device **500** includes a plurality of tubes **640** that are arranged in a telescopic configuration. The tubes **640** may have a circular cross section, or other cross sectional shapes in other embodiments. During use, the telescopic tubes **640** are placed around the elongate member **490**. As the drivable assembly **184** is advanced distally, the tubes **640** retracts relative to each other to form a shorten configuration. As the driver is moved proximally, the tubes **640** extends out of their respective neighboring tubes **640** to form a lengthen configuration. The elongate member **490** is housed within the lumen formed collectively by the tubes **640**, and is prevented from buckling by the wall of the tubes **640**. It should be noted that at the larger tubes **640** location, the elongate member **490** may not initially be in contact with the wall of the tubes **640**. However, as the elongate member **490** is being compressed, the elongate member **490** will bend slightly due to the axial compression force applied on the elongate member **490**. The bending of the elongate member **490** will bring the elongate member **490** into contact with the wall of the relatively larger tubes **640**. When this happens, the tubes **640** will prevent the elongate member **490** from bending further, and will prevent the elongate member **490** from catastrophic buckling.

FIGS. **65**D-**65**G illustrates an implementation of the anti-buckling device **500** of FIG. **65**A in accordance with some embodiments. As shown in FIGS. **65**F and **65**G, each tube **640** has a stopper **641** at one end, and another stopper **642** at the opposite end. The stoppers **641**, **642** are configured to couple the tubes **640** together, and prevent the tubes **640** from being detached from each other.

FIG. **65**B illustrates a variation of the anti-buckling device **500** of FIG. **65**A, particularly showing the tubes **640** being arranged from the smallest size to the largest size in the proximal-to-distal direction.

FIG. **65**C illustrates another variation of the anti-buckling device **500** of FIG. **65**A, particular showing the tubes **640** being arranged from the largest size at one end to the smallest size in the middle section, and then to the largest size again to another end.

In the above embodiments, the anti-buckling device **500** may be provided on a robotic catheter when the drive assembly for the catheter is at the proximal end of the catheter. However, in other embodiments, the drive system may be provided at the distal end of the catheter for "pulling" the flexible catheter rather than "pushing" it. FIG. **66**A illustrates a drive device **500** that provides an anti-buckling feature in accordance with other embodiments. The device **500** includes a pair of rollers **660** that grip against the elongate member **490** at a distal location that is close to the incision site. The device **500** also includes mechanical linkage **662** connecting the rollers **660** to the drivable assembly **184**. During use, the drivable assembly **184** may be advanced distally to move the elongate member **490** into the incision site. When this occurs, the drivable assembly **184** will actuate the rollers **660** to apply tension to the elongate member **490**. This will prevent the elongate member **490** from being compressed (or from being compressed excessively), and prevent the elongate member **490** from buckling.

FIG. **66**B illustrates another drive device **500** that provides an anti-buckling feature in accordance with other embodiments. The device **500** includes a first pair of fingers **670*a*** for gripping against the elongate member **490** at a distal location that is close to the incision site. The device **500** also includes a second pair of fingers **670*b*** for gripping against the elongate member **490** at a distal location that is close to the incision site. The system **500** also includes mechanical linkage **672** connecting the first and second pair of fingers **670*a***, **670*b*** to the drivable assembly **184**. During use, the drivable assembly **184** may be advanced distally to move the elongate member **490** into the incision site. When this occurs, the drivable assembly **184** will alternately actuate the first and second pairs of fingers **670*a***, **670*b*** in accordance to a predetermined algorithm to apply tension to the elongate member **490**. This will prevent the elongate member **490** from being compressed (or from being compressed excessively), and prevent the elongate member **490** from buckling.

In some embodiments, the algorithm for controlling the pairs of fingers **670*a***, **670*b*** may be as follows: (1) Actuate first pair to grip the elongate member **490**, (2) translate the first pair along the longitudinal axis of the elongate member **490** to pull the elongate member **490**, (3) actuate the second pair to grip the elongate member **490**, (4) release the first pair, (5) translate the second pair along the longitudinal axis of the elongate member **490** to pull the elongate member **490**, (6) move back the first pair by some distance, (7) actuate the first pair to grip the elongate member **490**, (8) translate the first pair along the longitudinal axis of the elongate member **490** to pull the elongate member **490**, (9) move back the second pair by some distance, and repeat (3)-(9) to move the elongate member **490** until the elongate member **490** is desirable positioned.

FIGS. **67**A-**67**C illustrate another anti-buckling device **500** in accordance with other embodiments. The device **500** includes support members **510** that form into a scissor-like configuration. The device **500** may optionally include another set of support members **512** next to the support members **510**, as similarly described previously. The device **500** includes a plurality of holders **540** that are coupled to the support members **510**, wherein each holder **540** includes an opening for accommodating an elongated member **490** (e.g., a sheath, catheter, etc.). As shown in the figure, the device **500** further includes another set of support members **514**. As illustrated in FIGS. **67**B-**67**C, the support members **510**, **514**, holder **540**, and coupler **516** form a parallelogram, which allows the holder **540** and coupler **516** to be maintained parallel relative to each other as the support members **510**, **514** rotate. Since all of the holders **540** are maintained in parallel relative to their respective adjacent couplers **516**, all of the holders **540** are also maintained in parallel relative to each other as the support members **510**, **514** rotate to collapse or extend the device **500**. The above configuration is advantageous because by preventing the holders **540** from rotating relative to each other, the device **500** provides a higher anti-buckling resistance for the elongated member **490** (i.e., it will be harder to buckle the elongated member **490**). This is because when the holders **540** stay aligned relative to each other, the buckling load of the elongated member **490** is $4\pi^2EI/L^2$. On the other hand, when the holders **540** are allowed to freely rotate relative to each other, the buckling load of the elongated member **490** is π^2EI/L^2. Therefore, the elongated member **490** can undergo four times as much compressive force when the holders **540** are rotatably constrained than when the holders **540** are freely rotatable relative to each other.

As shown in the above embodiments, the device **500** is advantageous because it shortens the unsupported length of the elongate member **490**, thereby preventing the elongate member **490** from buckling during use. The device **500** is also advantageous because it provides anti-buckling feature from outside the elongate member **490**, and thus, obviating the need to modify the construction of the elongate member **490**. Also, embodiments of the device **500** described herein provide support(s) along the length of the elongate member **490** in all circumferential directions at the location of the support(s). This has the benefit of preventing the elongate member **490** from buckling in any direction during use.

Although embodiments of the anti-buckling/drive device **500** have been described with reference to the device **500** being used at certain location of the robotic system, in other embodiments, one or more of the embodiments of the device **500** may be used to support any flexible elongate member anywhere in the robotic system, including the flexible elongate member between the stabilizer **502** and the drivable assembly **184**, the flexible elongate member between the drivable assembly **184** and the drivable assembly **182**, or any other member that needs support to prevent the member from buckling.

Also, although embodiments of the anti-buckling device **500** have been described with reference to a medical robotic system, it should be noted that the anti-buckling device **500** described herein may be used to provide anti-buckling feature for any medical device having an elongate and flexible configuration. For example, in other embodiments, embodiments of the anti-buckling device **500** described herein may be used to support any flexible tool in the field of medicine, such as an endoscope, a flexible grasper, laser fibers, etc.

Also, one or more of the embodiments of the anti-buckling device **500** described herein may be used as a distance measurement tool. For example, in some embodiments, a pull string attached to a spring and an encoder may be used to track the displacement of the anti-buckling device **500**. In other embodiments, an encoder may be attached to any of the joints at the anti-buckling device **500** to measure the angle of a link (or links), and a processor may then calculate the overall length of the anti-buckling device **500** based on the measured angle. In other embodiments, an optical device may be configured to take an image of at least a portion of the anti-buckling device **500** (or the entire anti-buckling device **500**), and the length of the anti-buckling device **500** may then be determined (e.g., by a processor) using the image. In still further embodiments, a short stroke LVDT or similar linear encoder may be used to measure a displacement between any two links, and the processor may then calculate the overall length of the anti-buckling device **500** using the measured displacement. In further embodiments, an ultrasound transducer may be used to measure a relative displacement between two links, and the processor may then calculate the overall length of the anti-buckling device **500** using the measured displacement.

In addition, in one or more of the embodiments of the anti-buckling device **500**, the device **500** may further include a motor coupled to any one of the joints. In such cases, the motor may be activated to turn the joint, thereby extending or collapsing the anti-buckling device **500**. In other embodiments, a linear motor may be coupled between two joints or between two support members. In such cases, the linear motor may be operated to extend or collapse the anti-buckling device **500**. For example, in other embodiments, any of the joints **528** may be fixed relative to a global system. In such cases, the proximal end of the anti-buckling device **500** may be actuated (e.g., by linearly translating a support member **510**/**512**/**514**, or by rotating a joint that couples to an end of a support member **510**/**512**/**514**). In response to such actuation, the distal end of the anti-buckling device **500** will translate distally. The amount of distal translation by the distal end of the anti-buckling device **500** will depend on which of the joints **528** is fixed. Fixing a joint **582** that is closer to the proximal end would allow the distal end of the anti-buckling device **500** to move a relatively greater distance in response to a small translation of the proximal end of the anti-buckling device **500**, but such configuration may require a relatively larger actuating force to be applied at the proximal end (and the force transmitted to the distal end is relatively small compared to the force applied at the proximal end). On the other hand, fixing a joint **582** that is closer to the distal end would allow the distal end of the anti-buckling device **500** to move a relatively small distance in response to a large translation of the proximal end of the anti-buckling device **500**, but such configuration may require a relatively small actuating force to be applied at the proximal end (and the force transmitted to the distal end is relatively large compared to the force applied at the proximal end). In one or more of the embodiments described herein, the elongate member **490** may be coupled to the anti-buckling device **500**, the anti-buckling device **500** may be used to move the elongate member **490** proximally and distally. For example, in some embodiments, the distal end of the elongate member **490** may be coupled to the distal end of the anti-buckling device **500**.

As illustrated in the above embodiments, the anti-buckling device utilizes a scissor-like mechanism that provides a 1:1 motion for the elongate member **490**. That means when the proximal end of the member **490** is advanced distally by a distance, the distal end of the member **490** will be advanced by the same distance. Also, when the proximal end of the member **490** is retracted proximally by a distance, the distal end of the member **490** will be retracted by the same distance. This is advantageous over a system that does not have any anti-buckling mechanism, in which case, advancement of the proximal end of the elongate member by a distance may not result in advancement of the distal end of the elongate member by the same distance (because the elongate member may sag or buckle). Also, due to sagging or buckling, retraction of the proximal end of the elongate member by a distance may also not result in retraction of the distal end of the elongate member by the same distance (because the sagged or buckled section needs to be straighten out before the distal end of the elongate member may be pulled proximally). Accordingly, embodiments of the anti-buckling mechanism described herein provides a support frame that has no hysteresis between insert and withdrawal of the elongate member.

Also, in some embodiments, the compressed length of the anti-buckling device may be at least 5 times shorter than its extended length. In other embodiments, the ratio between the compressed length and the extended length may have any values.

Also, as illustrated in the above embodiments, the anti-buckling device provides high lateral stiffness to support an elongate member laterally, while providing a low axis stiffness so that the anti-buckling device may be compressed in response to a decrease in length of the elongate member as the elongate member is being advanced distally. Thus, the anti-buckling device does not deflect laterally (e.g., in one plane, or in two planes that form an angle relative to each other), and can be compressed in response to axial force.

VII. Lubrication Mechanism

In one or more of the embodiments described herein, the anti-buckling device **500** may further include a lubrication system for lubricating at least a portion of the elongate member **490**. FIG. **68** illustrates a lubricating system **700** attached to one end (e.g., the distal end) of the anti-buckling device **500**. The lubricating system **700** includes a container **702** for housing fluid, such as saline, and an absorption material **704** located in the housing for absorbing the fluid and applying the fluid to the elongate member **490**. The container **702** is coupled to the anti-buckling device **500** via a coupler **710**. The lubricating system **700** also includes an introducer for allowing the elongate member **490** to be inserted therethrough. In the illustrated embodiments, the coupler **710** has an opening for allowing the elongate member **490** to extend therethrough. The elongate member **490**, which may be a sheath, a catheter member, or a combination of both. In some embodiments, the elongate member **490** may optionally include a hydrophilic coating so that the elongate member **490** may interact (e.g., dissolve) with the saline. The dissolved coating becomes a lubricant for lubricating the elongate member **490** (which may allow the elongate member **490** to slide easily relative to object(s) that it comes in contact with—e.g., bodily tissue, supports of anti-buckling device, etc.). In other embodiments, the sterile fluid in the container **702** may itself be the lubricant, in which case, the lubricant is applied directly onto the elongate member **490** by the absorption material **704**. During use, fluid (e.g., saline) is placed in the container **702**, or may be applied directly to the absorption material **704**. The elongate member **490** is then inserted through the anti-buckling device **500**, and is advanced through the absorption material **704** that is located in the container **702**. As the elongate member **490** is advanced through the absorption material **704**, the absorption material **704** applies the fluid onto the surface of the elongate member **490**, thereby lubricating the elongate member **490**. The lubricant on the surface of the elongate member **490** allows the elongate member **490** to more easily slide relative to objects (e.g., tissue, introducer, etc.) that it comes in contact with during a medical procedure. The lubricating system **700** is advantageous in that it automatically applies lubricant onto the elongate member **490** as the elongate member **490** is advanced through the lubricating system **700**.

FIG. **69** illustrates another lubricating system **700** in accordance with other embodiments. The lubricating system **700** includes a bladder **730** attached to a distal end of the anti-buckling device **500**. The lubricating system **700** further includes a luer lock **732** with a check valve **734**, which allow a syringe to fill the bladder **730** with fluid (e.g., saline). In particular, the check valve **734** is configured so that when the syringe is not coupled to the bladder **730**, fluid inside the bladder **730** is prevented from escaping out of the bladder **730** through the check valve **734**. When the syringe is coupled to the bladder **730**, the check valve **734** is pushed open by the syringe, thereby allowing the syringe to deliver the fluid into the bladder **730**. The lubricating system **700** also includes a flow restrictor **736** at the bottom of the bladder **730** for allowing fluid to be applied onto the surface of the elongate member **490** in a controlled manner. In some embodiments, the elongate member **490** may optionally include a hydrophilic coating so that the elongate member **490** may interact (e.g., dissolve) with the saline. The dissolved coating becomes a lubricant for lubricating the elongate member **490**. In other embodiments, the fluid in the bladder **730** may itself be the lubricant, in which case, the lubricant is applied directly onto the elongate member **490** by the flow restrictor **736**.

In other embodiments, the lubricating system **700** of FIG. **69** may optionally further include a brush **740** attached to the bottom of the flow restrictor **736** (FIG. **70**). During use, the brush **740** applies the fluid from the bladder **730** onto the elongate member **490**. In other embodiments, the device **700** itself may function as an applicator. In such cases, the user may hold the applicator **700** and may apply fluid in the bladder onto the surface of the elongate member **490** before it is inserted into a patient. The fluid may interact with a hydrophilic coating on the elongate member **490** to form lubricant. Alternatively, the fluid itself may be lubricant that is applied directly onto the elongate member **490**.

In other embodiments, the lubricating system **700** may include a container (e.g., saline bag) **750** that is compressed by a pressure cuff **752**, and fluid from the container **750** is then routed to the drivable assembly **184** (FIG. **71**). In the illustrated embodiments, the drivable assembly **184** has internal plumbing and a flow restricting nozzle that would allow droplets to escape. As droplets are escaped from the drivable assembly **184**, they travel down the body of the elongate member **490**. In some cases, the elongate member **490** may be oriented at an angle **756** that is at least 15° relative to a horizontal axis, so that the droplets may flow down the elongate member **490** more easily. The droplets travelling down the body of the elongate member **490** will reach eyelets (e.g., AB eyelets) **754** that are placed around the elongate member **490**. Each eyelet **754** is configured to capture a small amount of fluid so that the elongate member **490** can absorb later. As more and more droplets leave the drivable assembly **184**, all of the eyelets **754** will eventually be filled up, and the elongate member **490** will be completely hydrated. In some embodiments, each eyelet **754** has an optimized surface area (or pressure head to viscosity ratio) for capturing a desired amount of fluid. The eyelets **754** may be coupled to the anti-buckling device **500** in some embodiments, in which case, the eyelets **754** may be considered to be components of the anti-buckling device **500**. For example, each eyelet **754** may be implemented at a respective holder **540** in the anti-buckling device **500**. Also, in some embodiments, the holders **540** themselves may be considered to be the eyelets **754**. In other embodiments, the eyelets **754** may be considered components of the lubricating system **700**.

In other embodiments, a hydrogel **768** may be manually applied onto the elongate member **490** via a gauze or cotton pad at several discrete locations through openings **770** of the anti-buckling device **500** (FIG. **72**). As the anti-buckling device **500** is extended or collapsed, the hydrogel **768** is spread out along the length of the elongate member **490** through the holders **540**. In some embodiments, the holders **540** have eyelets that store a small amount of hydrogel for later use.

In further embodiments, the lubricating system **700** may include a gel compartment **780** proximal to an incision site for applying gel to the elongate member **490** (FIG. **73**). The gel compartment **780** includes an inlet **782** for filling the compartment **780** with a gel substance **784**. During use, as the elongate member **490** is inserted distally, it picks up the gel substance **784**. In some embodiments, the elongate member **490** may optionally include a hydrophilic coating so that the elongate member **490** may interact (e.g., dissolve) with the gel. The dissolved coating becomes a lubricant for lubricating the elongate member **490**. In other embodiments, the gel **784** may itself be the lubricant, in which case, the lubricant is applied directly onto the elongate member **490** by the gel compartment **780**. In some embodiments, the gel compartment **780** may be coupled to a distal end of the anti-buckling device **500** through an adaptor **786**. Also, in some embodiments, if the elongate member **490** includes a sheath surrounding a catheter member, the gel compartment **780** may be placed proximal to the introducer sheath.

FIG. **74** illustrates another lubricating system **700** in accordance with other embodiments. The lubricating system **700** includes a collapsible tube **800** that contains gel **802**. The lubricating system **700** also includes one or more inlets in fluid communication with the tube **800** for delivering the gel **802** into the tube **800**. In the illustrated embodiments, the collapsible tube **800** is incorporated into the center of the anti-buckling device **500**. During use, the elongate member **490** is inserted through the collapsible tube **800** at the anti-buckling device **500**. The inlet(s) **804** is then used to deliver gel into the tube **800**. The anti-buckling device **500** is then extended and collapsed several times to evenly spread out the gel onto the surface of the elongate member **490** before the elongate member **490** is inserted into the patient. In some embodiments, the collapsible tube **800** may be implemented using a rigid telescoping tube, a flexible accordion tube, or a bellow.

FIG. **75** illustrates another lubricating system **700** in accordance with other embodiments. The lubricating system **700** includes a plurality of pockets **820**, wherein each pocket **820** has a nozzle **822** that points towards the elongate member **490**. The pockets **820** may be made from a resilient material, such as polyurethane, and may be attached at several locations (e.g., at joints between two support members) at the anti-buckling device **500**. In the illustrated embodiments, mini pouches of hydrogel are contained inside the pockets **820**. During use, the closing action of the anti-buckling device **500** squeezes the pockets **820** down to eject the gel out of the pockets **820** and onto the surface of the elongate member **490**. The anti-buckling device **500** may be extended and collapsed to distribute the gel through eyelets (e.g., holders **540**) along the elongate member **490**.

In other embodiments, the lubricating device **700** may be a drape made from a resilient material, such as polyurethane. Gel is applied to one side of the drape, and the drape is used to apply the gel onto the elongate member **490**, the anti-buckling device **500**, or both. For example, in some embodiments, the elongate member **490** together with the anti-buckling device **500** may be covered by the drape, and the drape is used to apply the gel onto the elongate member **490** and/or the anti-buckling device **500**. The drape is then removed from the elongate member **490** and/or the anti-buckling device **500** before use of these devices. The anti-buckling device **500** may be extended and collapsed to distribute the gel through eyelets (e.g., holders **540**) along the elongate member **490**.

FIGS. **76-77** illustrate another lubricating device **700** in accordance with other embodiments. The lubricating device **700** includes a stabilizing device **840** with a base for attachment to the patient or a bed, and a coupling **842** that joins the anti-buckling device **500** to the stabilizing device **840**. The stabilizing device **840** is configured to limit the motion of the distal end of the anti-buckling device **500** as the elongate member **490** is introduced and retracted relative to the patient. In some embodiments, as the catheter is being inserted and retracted, the stabilizer may be subjected to loads that may create a displacement in the direction of the catheter motion. In the illustrated embodiments, the lubricating device **700** includes a small membrane filled with fluid or gel at the base of the stabilizer **840**, which would be actuated by the displacement of the stabilizer **840**. The hydrating fluid would be delivered directly through the coupling **842**, or can be delivered elsewhere by incorporating delivery conduits or a spraying mechanism.

FIG. **78** illustrates another lubricating device **700** in accordance with other embodiments. The lubricating device **700** includes a container **860** containing fluid or gel. The container **860** is coupled to the stabilizer **502**, which is described previously. As the elongate member **490** is being inserted into the patient's skin, the elongate member **490** is extended through the container **860**, which applies the fluid or gel onto the elongate member **490**. The fluid or gel may directly lubricate the surface of the elongate member **490**. Alternatively, the fluid or gel may react with an optional hydrophilic coating on the elongate member **490** to form a lubricating substance.

In further embodiments, the lubricating device **700** may include a membrane **890** that encapsulates the anti-buckling device **500**, wherein the membrane **890** is filled with fluid or gel during use (FIG. **78**A). The membrane **890** may have a bellow configuration, which allows the membrane **890** to extend and contract together with the anti-buckling device **500**.

It should be noted that although the term "catheter" and the term "sheath" are used to describe some of the embodiments of the components, these terms should not be limited to the configuration shown. For example, in other embodiments, what was referred to as a "catheter" may also be called a "sheath" and vice versa. Also, in some embodiments, the term "catheter" or the term "sheath" may refer to two or more tubular structures that are arranged telescopically, or that are coupled to each other.

VIII. Guidewire Manipulator

Typical manual surgical procedures include the use of a guide wire curved at its distal tip so that the guide wire can be navigated through tortuous anatomy by hand-actuated roll and insert motion at its proximal end. Once in place, catheters can be inserted co-axially over the guide wire, the guide wire can be retracted and removed, and the catheter can remain in place providing a delivery device for other minimally invasive tools.

Guide wires or distal protection devices for certain vascular and other interventions, may be difficult to position due to their relatively minimal navigation degrees of freedom from a proximal location, and the tortuous pathways through which operators attempt to navigate them. Additionally, minimally invasive medical procedures can be time consuming and physically demanding on an operator causing not only operator fatigue but an excessive amount of exposure of the operator to radiation fields. Providing robotically and remotely precision controlled additional navigation and operational functionality options for minimally invasive interventions, would be useful.

Certain variations of systems as shown in FIG. **1** may include additional remote motorized control of other pull wire or non pull wire elongate members such as guide wires, which utilize roll and insert motions at their proximal ends to steer their distal tips. Different variations of elongate member manipulators which can provide motorized actuation of a guide wire or other elongate member are herein described. Many of the manipulator assemblies disclosed herein can be used to provide any motorized roll and insert or retraction actuation of any elongate instrument or member including but not limited to ablation probes, needles, scissors, clamps, forceps, graspers, guide wires, catheters, endoscopes, and other minimally invasive tools or surgical instruments.

FIGS. **79**A-**79**D illustrate different views of a variation of an elongate member manipulator **1100**. The elongate member manipulator **1100** includes a set of right and left motor actuated rotary members **1124**, **1104**. The rotary members can be used to robotically control the insertion and retraction of an elongate member, e.g., a guide wire, along a longitudinal axis of the elongate member and/or the roll or twist of the elongate member about a longitudinal axis of the elongate member. In this variation, the rotary members are in the form of cylinders or feed rollers. However, the rotary members may include any other device suitable for providing rotary motion including belts.

As shown in FIG. **79**A, the elongate member manipulator **1100** includes a right roller assembly **1122** and a left roller assembly **1102**. Each roller assembly provides rotation and up-down or axial translation to their respective feed rollers **1124**, **1104**. The left roller assembly **1102** includes the left spline actuator **1106** and the left leadscrew actuator **1108**. The right roller assembly **1122** includes a right spline actuator **1126** and a right leadscrew actuator **1128**.

As illustrated in FIG. **79**C, (a cross sectional view of the elongate member manipulator **1100**), the internal elements of the left spline actuator **1106** may be identical to the internal elements of the right spline actuator **1126**. Also, the internal components of the left leadscrew actuator **108** may be identical to the internal components of the right leadscrew actuators **1128**. Thus both right and left spline actuators **1126**, **1106** may include a spline shaft **1174**, coupled to a spline nut **1176** which is driven by a gear train which will be described in further detail below. Similarly, the right and left leadscrew actuators **1128**, **1108** may include a leadscrew shaft **1184**, coupled to a leadscrew nut **1186**, driven by a similar gear train.

The spline nut **1176** and leadscrew nut **1186** may be sized such that two axially adjacent gears can create a gear stack that covers the entire axial length of each nut. Thus the left spline actuator **1106** may include a left spline gear stack **1110**, which acts as one gear driving the spline shaft **1174** which in turn drives the left roller **1104**. The left leadscrew actuator **1108** may also have a similar left leadscrew gear stack **1114** which functions in a similar manner. In alternative variations, a smaller spline nut and smaller leadscrew nut may be utilized allowing for a single gear to be used as opposed to a gear stack.

The right roller assembly **122** may include gears that are driven (in a manner as will be described below), and instead of stacking two adjacent gears, the right spline actuator **1126** can include a smooth shaft **1132** and a right spline output gear **1130**. The right leadscrew actuator **1128** can include a smooth shaft **1138** and a right leadscrew output gear **1136**. The right spline output gear **1130** and right leadscrew output gear **1136** are coupled to the spline shaft **1174** and leadscrew shaft **1184** respectively and the gears drive the motion of the roller **1124**.

In operation, the right and left rollers **1124**, **1104** may rotate at substantially the same rate but in opposite directions to facilitate insertion or retraction of an elongate member, such as the guide wire **1060** (shown in FIGS. **79**A-**79**B and **79**D). Idler gears may be used to couple the motion of the right and left actuator assemblies **1122**, **1102**.

As shown in FIG. **79**B the elongate member manipulator **1100** may include a right spline coupling gear **1134**, a left spline coupling gear **1135**, a right leadscrew coupling gear **1140** and a left leadscrew coupling gear **1141**. To rotate the rollers **1104**, **1124**, the left spline gear stack **1110** is driven by a spline belt **1112**, which in turn can be directly driven by a motor or driven indirectly by a series of gears, belts or pulleys (not shown). As previously described, this rotation will cause a direct rotation of the left roller **1104**. Simultaneously, the left spline gear stack **1110** may use the coupling gears to drive the right roller **1124** in an opposite direction to that of the left roller **1104**.

FIG. **79**D, shows a top view of the elongate member manipulator **1100** (the feed rollers are not shown for clarity). In this example, the left spline gear stack **1110** is driven in the CW direction **1150**, the left spline coupling gear **1135** will rotate in the CCW direction **1152**, rotating the right spline coupling gear **1134** in the CW direction **1150**, and the right spline output gear **1130** in the CCW direction **1152**. If all the gears are sized equally, the left spline gear stack **1110** and right spline output gear **1130** will rotate at the same rate in opposite directions, rotating the rollers **1104**, **1124** at equal rates in opposite directions, which would drive the guide wire **1060** in a forward propelling motion **1159**. Reversing the direction of the spline belt **1112** would reverse the directions of both the left spline gear stack **1110** and right spline output gear **1130**, and as a result, reverse the direction of rotation of the rollers **104**, **124**, thereby driving the guide wire in the reverse propelling motion.

The leadscrew actuators **1108**, **1128** may function in a similar manner but alternatively cause one roller to translate upwards while the other roller translates downwards at a substantially similar rate. This motion will drive the guide wire **1060** in a roll or torque motion. The clockwise or counterclockwise directions of roll are dependent on the direction of rotation of the leadscrew belt **1116**. Both insert/propelling motion and roll/torque motion can be accomplished with varying speed rates for each axis. The propelling and torque axes motions can be simultaneous, or they can be independent of each other.

FIG. **81** illustrates a cross sectional view of one variation of a roller actuator **1170** that may be utilized to provide motorized rotation and translation actuation of one or more rotary members, such as a feed roller. Such a roller actuator may be utilized to provide rotation and translation actuation of various rollers, including, for example, the rollers of elongate member manipulator **1100** described above.

The roller actuator **1170** includes a one or more spline actuators **1172** having a spline shaft **1174** coupled to a spline nut **1176** mounted on spline nut bearings **1178**. The spline nut **176** is rotated by a spline gear **1180** which can either be directly motor driven or indirectly motor driven via a series of gears, belts or pulleys (not shown). The spline shaft **1174** may be fixably coupled to a rotary member such as a feed roller **1104**, so that the rotation of the spline nut creates rotation of the feed roller. A single leadscrew actuator **1182** which includes a leadscrew shaft **1184**, leadscrew nut **1186**, leadscrew nut bearings **1188**, and a leadscrew gear **1190** is provided adjacently below the spline actuator **1172** to provide up-down translation of a feed roller. The leadscrew nut **1186** is driven by the leadscrew gear **1190** which can either be directly motor driven or indirectly motor driven via a series of gears, belts or pulleys (not shown). Rotation of the leadscrew nut **1186** lifts and lowers the leadscrew shaft **1184** and spline shaft **1174**, creating the up and down lift or axial translation of the feed roller.

In certain variations, the spline shaft **1174** and leadscrew shaft **1184** may be coupled so that rotation of one may cause rotation of the other. Because the spline shaft **1174** is constructed as a spline, it can be driven up and down by the leadscrew shaft **1184** without lifting the spline nut **1176**, spline bearings **1178**, or spline gear **1180**. To actuate only rotation of the feed roller, both spline nut **1176** and leadscrew nut **1186** may be rotated at the same rate. As a result, the leadscrew shaft **1184** will rotate at the same rate as the leadscrew nut **1186** so that no lift motion will occur. To actuate only lift of a feed roller, the leadscrew nut **1186** may be rotated without movement of the spline nut **1176**. Alternatively, simultaneous rotational and translational motion of a feed roller may be provided by slowing and speeding up the leadscrew nut **1186** relative to the spline nut **1176** or vice versa.

In an alternative variation, the spline shaft **1174** and the leadscrew shaft **1184** may not be coupled so that movement of the spline actuator **1172** and the leadscrew actuator **1182** are completely independent. Alternatively, the spline shaft **1174** and leadscrew shaft **1184** could be free to rotate independently by joining the two shafts in a ball and socket type configuration. Additional bearing support may be utilized in such a variation.

FIGS. **80**A-**80**B illustrate examples of feed rollers in use, showing how an elongate member, e.g., a guide wire **1060**, may be actuated by the feed rollers **1124**, **1104**. FIG. **80**A illustrates a top view of a pair of feed rollers **1124**, **1104** illustrating how the feed rollers can rotate about their axes in opposite directions **1152**, **1150** to drive a guide wire **1060** in a backwards propelling motion or a retract motion **1158**. The feed rollers can also be rotated in opposing directions to provide forward propelling or insert motion (not shown). FIG. **80**B shows a front view of the feed rollers **1124**, **1104** illustrating how the feed rollers can translate axially along their axes in opposite translation directions **1154** to torque or roll **1160** the guide wire **1060**.

Forward or reverse insert/retract motion **1158** is dependent on the direction of rotation **1152**, **1150** of the rollers **1124**, **1104** while clockwise or counter-clockwise roll motion **1160** is dependent on the direction of up and down linear or axial translation **1154** of the rollers **1124**, **1104**. Both insert/retract motion and roll motion can be accomplished with varying speed rates for each axis. The insert and roll actuations can be independent of one another, or they may occur simultaneously. Also simultaneous roll and insert actuation can be desirable in part because traditional manual procedures are performed in that manner. Currently physicians articulate and steer manual guidewires by inserting and rolling simultaneously resulting in more of a spiraling insertion. It can be desirable for robotic systems to emulate manual procedures for physician ease of use.

In alternative variations, insert motion can be provided by feed rollers while roll motion actuation may be provided by clamping the guide wire in a clamp mechanism and rolling the clamp mechanism. In this variation roll and insert motion may be alternated between insert and roll with typical clutching mechanisms that release grip from one actuator assembly while the alternate assembly provides actuation. For example, in a feed roller variation with clutching, feed rollers used to actuate insert may release the guide wire while actuators providing rotation to roll the guide wire. The release of the guide wire from one actuator during activation of the alternate actuator in systems which use feed rollers for insert but roll the guide wire with a separate mechanism allows the guide wire to overcome friction experienced from the feed rollers during roll actuation. If insert and roll are simultaneously actuated the wire may be gripped in the insert feed rollers which could result in the stripping or winding up the wire.

Systems which clutch between insert and roll actuators typically release grip of the guide wire by one actuator to allow the alternate actuator to grip the guide wire. By releasing the wire, any tracking of guide wire position using encoders may be lost which could decrease the accuracy of position tracking. Also, additional actuators may result in a more complex or more costly system.

In certain variations, a guide wire **1060** may be loaded into the elongate member manipulator **1100** by being back or front loaded or fed into the feed rollers **1104**, **1124** while rotating the feed rollers **1104**, **1124** in an insert or retract motion.

In certain variations, the elongate member manipulator **1100** may be designed such that at least a portion of the elongate member manipulator **1100** remains in a sterile field. For example, the motors and drive mechanisms or drive components of the elongate member manipulator may be situated in a non-sterile field and a sterile drape could be placed in-between the drive components and the feed rollers. Thus, the elongate member, e.g., a guide wire, held by the feed rollers will remain sterile for insertion into a patient's anatomy. In certain variations, components of an elongate member manipulator which are meant to remain sterile may be disposable and/or the complexity of such components may be minimized in order to minimize or reduce overall costs of such disposable components or the elongate member manipulator.

Referring back to FIGS. **79**A-**79**C, one variation of a sterile drape **1070** used to create a sterile field that includes the feed rollers **1104**, **1124** and guide wire **1060** is illustrated. All other components could be positioned in a non-sterile field.

FIG. **82** shows an example of the sterile drape **1070** installed between the left feed roller **1104** and the spline shaft **1174**. The sterile drape **1070** may be designed such that the roller **1104** can be removeably replaceable where the drape **1070** could be placed over the spline shaft **1174** and the rollers could be installed over the drape in the sterile field. The sterile drape **1070** could have a sterile drape bushing **1072** that is fixably attached to the drape **1070**. The roller **1104** could be coupled to the bushing **1072** via a roller shaft **1105** extending through the bushing **1072** which is coupled to the spline shaft **1074** in the non-sterile field. The roller shaft **1105** and spline shaft **1074** could be coupled by keying each shaft to mate, thus allowing rotation of the spline shaft **1074** to cause a one to one rotation of the roller shaft **1105**. The key can be shaped as a hexagon, triangle, star, cross or any other shape. The roller **1104** may rotate relative to the bushing and may translate up and down like a piston. A fastener may be provided to secure the roller **1104** in place to prevent slippage in the axial direction. Alternatively, the roller shaft **1105** may be threaded and coupled to a threaded hole in the spline shaft **1174**. As the roller **1104** moves up and down, a left roller groove **1123** on the roller may create a labyrinth seal and maintain a sterile boundary between the bushing **1072** and roller **1104**. Optionally, an o-ring or lip seal can be placed between the bushing **1072** and roller **1104** to prevent fluid ingress and create an improved sterile boundary. The sterile drape **1070** could provide for a sterile interface for the right feed roller **1124** in the same manner.

FIGS. **83-83**A illustrate another variation of an elongate member manipulator **1200** which includes rotary members in the form of belts. The elongate member manipulator **1200** is shown mounted on an instrument driver **16**. The elongate member manipulator **200** may by utilized to feed an elongate member, such as guide wire **60**, co-axially into a guide catheter splayer **1052**. The guide wire **1060** may be fed into a support tube **1056** which subsequently feeds into the guide catheter splayer **1052**, and ultimately into a guide catheter (not shown). In certain variations, the elongate member manipulator may be mounted on the instrument driver along with a guide and/or a sheath splayer/catheter or the elongate member manipulator may be mounted alone. Optionally, the elongate member manipulator may be utilized to feed an elongate member, such as guide wire, co-axially into a sheath and or catheter. Optionally, the elongate member manipulator may be utilized to feed an elongate member, such as guide wire, directly into a patient's body or anatomy.

FIG. **84** illustrates the elongate member manipulator **1200** in an open hinged configuration. The elongate member manipulator can include a drive assembly and an elongate member holder. The components of the elongate member holder include a drive belt assembly **1210** and an idler belt assembly **1220**. Both belt assemblies include belts **1212**, **1222** with pulleys **1214**, **1224**. The drive pulley **1084** may be directly driven by an insert servo motor **1102** or other mechanism to turn the drive belt **1212**. The idler belt **1222** is free to rotate about the idler pulley **1224**. The belts may be constructed from various materials known to person having ordinary skill in the art. The belts may have various dimensions. For example, about 1" wide Texin® or silicon rubber, durometer 90A profiled timing belts may be utilized covering a length of about 4.5" from opposite outer diameter edges of the belt. Other variations may use alternative widths, other dimensions, and materials with alternative durometers for the belts. In one variation the belts can be constructed from any gamma sterilizable material which is well known in the art including but not limited to thermoplastics such as ABS or PET, fluoropolymers such as polyvinyl fluoride, polymides, polystyrenes, polyurethanes, polyesters, or polyesters. Optionally, bands or feed rollers could be used in place of belts.

As shown in FIGS. **85**A, **85**B and **85**C, the drive assembly can include an upper slide assembly **1234**, a lower slide assembly **1230**, an insert motor **1202**, and a roll motor **1204**, as well as a set of rails, a rack and a pinion (not shown here but described in detail below). In use, as illustrated in FIGS. **84** and **85**A, the upper slide assembly **1234** can hinge open a plurality of degrees for workflow clearance, the guide wire **1060** can be placed on the drive belt **1212**, and the elongate member manipulator **1200** or system can be closed so that the guide wire **1060** is held between the drive belt **1212** and the idler belt **1222**. This allows a guide wire to be loaded into the elongate member manipulator **1200** anywhere along the length of the guide wire **1060**, which may expedite the loading procedure instead of being restricted to load the wire by feeding the wire from the back of the system. Also the guide wire can be loaded when the belts are in any position. For example, the drive belt **1212** may be at an arbitrary position such that the drive motor **1202** does not require any type of initialization or homing before installation of the guide wire **1060**. Additionally a guide wire can be removed from the elongate member manipulator **1200** or system mid procedure if the operator desires to switch from using the robotic manipulator to manual control of the guide wire.

In alternative variations a guide wire can be backloaded into a manipulator. A back loaded guide wire would be retracted or pulled out of a patient's body before removing the guide wire from the manipulator to switch to manual control

To ensure that the upper slide assembly **1234** and lower slide assembly **1230** stay closed during operation, a captive screw **1254** can be used. A variation including a captive screw **1254** is shown in FIGS. **85**B-E which illustrate an isometric view of the elongate member manipulator **1200** with only the drive belt assembly **1210** shown (idler belt assembly not shown for clarity). FIG. **85**B illustrates the elongate member manipulator **1200** in an open position, FIG. **85**C illustrates the elongate member manipulator **1200** as it is partially closed, and FIG. **85**D shows the elongate member manipulator **1200** closed and locked. The captive screw **1254** remains captive with the upper slide assembly **1234** and locks into a threaded hole **1256** in the lower slide assembly **1230**. FIG. **85**E illustrates a cross section of the elongate member manipulator illustrating the operation of the captive screw **1254**. In alternative variations, a latch, fastener or other type of locking, fastening or latching mechanism may be used instead of a captive screw.

As illustrated in FIG. **85**A, once the guide wire **1060** is loaded and held between the drive belt **1212** and the idler belt **1222**, the insert motor **1202** drives the drive pulley **1214**, turning the drive belt **1212** and propelling the guide wire **1060** forward or backwards (insert or retract) depending on the rotational direction of the motor and pulley. With sufficient frictional pinching, gripping, pressing, or holding force holding the guide wire **1060** between the drive belt **1212** and idler belt **1222**, the idler belt **1222** will turn at the same rate as the drive belt **1212**, and the belts will hold the guide wire **1060** such that lateral linear movement or displacement of the guide wire relative to the belts may be eliminated, minimized or reduced.

FIGS. **86**A-**86**C illustrate various views of the elongate member manipulator **1200** showing various components of the elongate member manipulator that function to provide roll actuation of the guide wire **1060**. (Some components of the elongate member manipulator **1200** are hidden for clarity.)

FIG. **86**A illustrates an end view of the elongate member manipulator **1200**. FIGS. **86**B-**86**C illustrate perspective views of the elongate member manipulator **1200** providing different angles showing the lower slide assembly **1230** and the upper slide assembly **1234**. The lower slide assembly **1230** and upper slide assembly **1234** may each be attached to linear rails **1240**. The lower slide assembly **1230** includes the insert motor **1202** and a slip detection encoder **1204**. The drive belt assembly **1210** attaches to the lower slide assembly **1230** while the idler belt assembly **1220** attaches to the upper slide assembly **1234**. Both lower and upper assemblies **1230**, **1234** have a rack **1232**, **1236** that is coupled to a pinion **1238** driven by a roll motor **1206**. The roll motor **1204** is mounted stationary relative to the instrument driver so that when the pinion **1238** is turned, the slide assemblies **1230**, **1234** move or translate in opposing directions, driving both the drive belt assembly **1210** and the idler belt assembly **1220** in opposing translational directions **1154**. This motion will roll, rotate or torque the guide wire **1060** as shown by the arrow **1160**. Translation of the drive belt assembly **1210** and idler belt assembly **1220** in directions opposite those shown in FIG. **86**A would result in roll of the guide wire in the direction opposite that of arrow **1160**.

In an alternative variation (not depicted), either the upper or lower slide assemblies could be coupled to a leadscrew so that motorized rotation of the leadscrew would result in translation of one slide assembly relative to the other. Roll and insert can be independently actuated or actuated simultaneously as described previously.

When the elongate member manipulator **1200** is in a closed configuration holding the guide wire **1060**, a sufficient pinching force between the drive belt **1212** and idler belt **1222** may be necessary to provide adequate frictional force to actuate insert, or retraction, and/or roll of the guide wire **1060**. As various guide wires **1060** with varying wire diameters may be loaded into the elongate member manipulator **1200**, it may be desirable to adjust the pinching force such that the applied pinching force is high enough to provide for insert and roll actuation while low enough to prevent damage or buckling of the guide wire **1060**.

Thus, in certain variations, the upper slide assembly **1234** of an elongate member manipulator can include a hinge **1242** and a suspension mechanism **1244**. FIGS. **87**A-**87**B show a left side view of an elongate member manipulator **1200** with the suspension mechanism **1244** in an open and closed configuration respectively, while FIG. **87**C shows a cross section of the assembly **1234** with the suspension mechanism **1244**. The suspension mechanism **1244** may include a lever arm **1246**, a lever shaft **1248**, a lever spring **1250** and a tightening nut **1252**. The suspension mechanism **1244** may provide a mechanism by which the force applied by the lever spring **1250** to hold the guide wire between the idler belt assembly **1220** and the drive belt assembly **1210** may be adjusted in order to accommodate a variety of guide wire diameters while providing sufficient pinching force for a variety of guide wire diameters.

As illustrated in FIG. **87**B, the tightening nut **1252** may be used to control the swing of the lever arm **1246** to adjust the grip force between the upper slide assembly **1234** and the lower slide assembly **1230** to apply the necessary grip force for various wire diameters and to provide an increased force ratio for wire compression. By way of example but not limitation, if a 2 to 1 force ratio could be applied where a 20 lb wire load was required, a 10 lb spring would be applied to the lever. The range of guide wire diameters that could be accommodated for this example may range from about 0.014"-0.038".

FIGS. **88** and **89** illustrate a pair of elongate member brackets or wire holders **1260**, **1262** that can be used to prevent a guide wire **1060** or other elongate member from sliding or slipping laterally or in the direction of slide assembly or belt assembly translation while the guide wire or elongate member is being rolled or twisted. Such wire holders may hold or grip a guide wire in addition to or in place of the frictional pinching force provided by the rotary member, rollers or belts. FIG. **88** illustrates the elongate member manipulator **1200** with a pair of wire holders **1260**, **1262** where both the elongate member manipulator and the wire holders are in an open configuration. FIG. **89** illustrates the manipulator **1200** and wire holders **1260**, **1262** in a closed configuration.

The wire holders **1260**, **1262** may be in the form of simple clamps or other configurations that can open and close to load and hold the guide wire **1060** and/or the guide wire support tube **1056**. Cut outs in the holders may be sized to allow for the guide wire **1060** and/or the valve assembly **1352** to be held in place along a longitudinal axis of a belt assembly while also allowing the guide wire to move in a propelling motion or a roll motion without excess friction. In order to prevent or minimize any undesired slippage in the translation direction **1154** (See FIG. **86**A) during roll of the guide wire, which may result from the tolerance provided by such cut outs, dimensions of the wire holders can be varied. The wire holders may be designed to minimize or prevent such slippage in the translation direction while also minimizing or preventing propelling and/or roll friction. Additionally, lubricants could be used to minimize or prevent propelling and/or roll friction while still minimizing or preventing slippage in the translation direction.

Alternatively, some situations may require minimizing lubrication of the guide wire in order to provide adequate gripping of the wire. In one variation, as the guide wire is retracted or de-inserted from the patient, sections of the guide wire may become coated with blood or fluid. When the sections are retracted between the drive belt assembly **1210** and idler belt assembly **1220**, the guide wire **1060** may become slippery preventing the guide wire manipulator **1200** from adequately rolling and de-inserting the guide wire **1060**. Thus, an absorbent material (not shown) may be integrated or included into the wire holder **1260** to remove blood or fluid from the guide wire **1060** as it is retracted into the guide wire manipulator **1200**. In certain variations, the absorbent material could be integrated only in the distal wire holder **1260** and not the proximal wire holder **1262** since the length of guide wire proximal to the drive and idler assembly belts **1210**, **1220** is no longer engaged in the guide wire manipulator **1200**. In alternative embodiments the absorbent material can be integrated into both wire holders **1260**, **1262** or only the wire holder **1262** preventing any outside fluids from coating the guide wire during the insert forward propelling actuation motion as well or to provide additional fluid removal of the guide wire during retraction. The absorbent material can included but is not limited to any type of sponge, wicking cloth, or polymer. Alternatively, a wiper mechanism can be integrated into the wire holders **1260**, **1262**.

In addition to the slippage that may occur during roll motions, a guide wire **1060** or other elongate members may also be susceptible to slippage between the drive belt **1212** and idler belt **1222** in the direction of insertion or retraction motion while the guide wire is being propelled forward or backward, despite maximizing pinching force and optimizing belt materials. Roll and/or insert motors **1202**, **1204** can be provided with encoders to measure the commanded insert and roll of a guide wire. To help improve the accuracy of this measurement, a mechanism for slippage detection during insert or retraction may be provided.

Referring back to FIG. **84**, in certain variations, the elongate member manipulator **1200** may include a drive side slip roller **1216** and idler side slip roller **1226** for guide wire insertion or retraction tracking. One or more of the drive and idler slip rollers **1216**, **1226** may be decoupled from motion of the drive and idler belts **1212**, **1222**. The drive roller **1216** is shown directly coupled to an encoder **1206** (illustrated in FIG. **85**) for guide wire slip detection. The drive side slip roller **1216** can be constructed from a harder material, e.g., PET, and the idler side slip roller **1226** can be constructed from a softer material, e.g., an open celled rubber. The harder PET will not deform from contact with the guide wire **1060** preventing the outside diameter of the drive side slip roller **1216** from varying. Since the insertion or retraction distance may be calculated from encoder counts (where encoders are used) and roller diameter, it is important that the roller coupled to the encoder be non-deformable material such as PET. Conversely, the softer material, e.g. the open celled rubber could allow for compression compliance which will assist with guide wire grip. The combination of materials allows for a tight grip on the guide wire **1060** during insertion/retraction, but provides for a smooth slip during roll. Alternative materials could be used to allow for this smooth slip while still providing adequate gripping of the wire during insertion and retraction. Any type of gamma sterileizable material can be used which can be chosen based on durometer. Alternatively, the drive side slip roller **1216** may be constructed form a softer material and the idler side slip roller **1226** may be constructed from a harder material and the encoder may be should be coupled to the idler slip roller **1226**.

In order to maximize workflow while keeping the guide wire **1060** and belt assemblies **1210**, **1220** in the sterile field, a mechanism that allows for easy removal and replacement of the sterile components, including the guide wire and belt assemblies, may be provided. The belt assemblies may be detachable or removable from the slide assemblies and/or remaining components of the elongate member manipulator such that a drape or other sterile barrier may be installed or inserted between the sterile components, e.g., the belt assemblies, and the non-sterile components, e.g. the slide assemblies. Additionally, the sterile components may be disposable. Accordingly, the complexity of the sterile components or assembly of the elongate member manipulator may be minimized to reduce cost, and many components of the elongate member manipulator, such as certain motors, gears, capstans, etc., may be designed or configured such that they remain in the non-sterile field.

FIGS. **90**A-**90**C illustrate the drive belt assembly **1210** and the idler belt assembly **1220** as sterile assemblies of minimal complexity having pulleys and belts, where the assemblies can be removed and replaced easily. FIG. **90**A illustrates the elongate member manipulator **1200** with the drive belt assembly **1210** and the idler belt assembly **1220** removed or detached from the slide assemblies **1230**, **1234**. The belt assemblies may include a drive shaft **1264** having a cross pin **1266** to key into socket **1268** provided in the slide assemblies **1230**, **1234**. Alternatively a spline or taper element could be used. A captive nut **1270** may be attached to the disposable drive and idler belt assemblies **1210**, **1220** and remain in the sterile environment. FIG. **14**B shows a cross section of the elongate member manipulator where the drive belt assembly **1210** is fully installed and the idler belt assembly **1220** partially installed in the slide assemblies while FIG. **90**C shows the same cross section with both belt assemblies **1210**, **1220** fully installed in the slide assemblies.

FIGS. **91**A-C illustrate another variation of an elongate member manipulator **1300**. The elongate member manipulator **1300** may be mounted to a manipulator mounting bracket **1058** which is mounted to the instrument driver **1016**. The elongate member manipulator **1300** may be utilized to feed an elongate member, such as guide wire (not shown), co-axially into a support tube **1056** which subsequently feeds into the guide catheter splayer **1052**, and ultimately into a guide catheter **1054**. In certain variations, the elongate member manipulator **1300** may be mounted on the instrument driver **1016** along with a guide and/or a sheath splayer/catheter or the elongate member manipulator **1300** may be mounted alone.

FIGS. **91**D-H illustrate various views of the elongate member manipulator **1300**. FIGS. **91**D-E show perspective views of the elongate member manipulator **1300** in a closed configuration, FIG. **91**F shows a perspective view of the elongate member manipulator **1300** in an open configuration, and FIGS. **91**G-H show right and left side views of the elongate member manipulator **1300** in a closed configuration.

The elongate member manipulator **1300** may include an upper slide assembly **1334**, a lower slide assembly **1330**, a drive belt assembly **1310**, an idler belt assembly **1320**, an insert motor **1302**, a roll motor **1304**, and an elongate member support **1332**. The insert motor **1302** may be fixably mounted to the upper slide assembly **1334** while the roll motor **1304** may be fixably mounted to a manipulator base **1306** or to the lower slide assembly **1330**. The elongate member support **1332** may also be mounted to the manipulator base **1306** or lower slide assembly **1330** using one or more screws **1336** or other attachment mechanisms. The drive belt assembly **1310** may be removeably coupled to the upper slide assembly **1334** while the idler belt assembly **1320** may be removeably coupled to the lower slide assembly **1330** both using one or more screw assemblies **1372** or other attachment mechanisms.

FIGS. **92**A-B illustrate perspective views of a variation of an idler belt assembly **1320**. In this variation, three small, separate idler belts **1322** are free to rotate about passive idler pulleys **1324** rotatably mounted to an idler frame **1326**. The multiple small idler belts **1322** may be spaced apart allowing the elongate member support **1332** to be inserted, positioned or to extend between two or more of the belts **1322** as shown in FIG. **91**F. In certain variations, two or more idler belts may be utilized in an idler belt assembly.

FIGS. **93**A-**93**D illustrate perspective top and bottom views of a variation of a drive belt assembly **1310**. In this variation, the serpentine belt **1312** is snaked in a "serpentine" like or weaving manner around one or more of the drive pulley **1319**, the serpentine idler pulleys **1314** and the reverse idlers **1315**, which are each rotateably mounted to the drive frame **1316**. This provides a mating, multiple segmented belt that may make contact with the multiple small idler belts **1322** while still providing clearance for the elongate member support **1332**. The drive pulley **1319** may be fixably coupled to a drive shaft **1318**. Materials for various components for both the idler belt assembly **1320** and drive belt assembly **1310** could include but are not limited to Polyurethane 90A for the belts **1212**, **1322**, and anodized Al 6061-T6 for the frames **1316**, **1326** and pulleys (**1315**, **1315**, **1319**, **1324**). Other similar materials may be utilized.

FIGS. **94**A-**94**B show another variation of an elongate member support **1332** that may be used in the elongate member manipulator **1300**. FIG. **94**B illustrates a cross-sectional top view of the elongate member support **1332**. Certain portions of the support **1332** or the entire support **1332** may be sterilizable. The support **1332** may include a support body **1334** and one or more screws **1336** embedded in support rods **1338** which are controlled by screw knobs **1340** may also be provided on the support **1332**. The support body **1334** may have arms or protrusions **1341** and/or grooves **1342** for holding an elongate member. In one variation, the elongate member support **1332**, the support rods **1338** and/or the screw knobs **1340** may be made of a softer material such as a PET (poly ethylene terephthalate) thermoplastic, while the screws

1336 may be made of stainless steel. In alternative variations, the above components may be made from a variety of materials and the materials could vary based on desired hardness of materials as well as costs.

During operation, the upper slide assembly 1334 may hinge or rotate open as shown back in FIG. 91F to allow for the guide wire 1060 to be installed onto the elongate member support 1332. The elongate member support 1332 provides a holder for the guide wire 1060 while centering the guide wire 1060 in a desirable position. The multiple belt configuration provided by the idler belts 1322 allows for positioning and clearance of the elongate member support 1332 in between the idler belts 1322. The positioning of the elongate member support 1332 may be such that the guide wire 1060 is supported while still being adequately held between the multiple small idler belts 1322. Also various elongate member supports could be provided each with different sized grooves to allow for use of varying sized guide wires. The elongate member supports may also be sterile and/or disposable or they may be non-sterile. For example, the elongate member support 1332 could be provided as a sterile disposable and be removed and replaced with an alternatively sized elongate member support if a different sized guide wire was necessary mid-procedure.

FIG. 94C illustrates an alternative perspective view of the elongate member manipulator 1300 with an insert motor cover 1303 mounted thereon, FIG. 94D illustrates the same perspective view with the insert motor cover removed, and FIG. 94E illustrates a zoomed in view of the elongate member manipulator 1300 with the motor cover 1303 removed displaying the insert motor 1302 mounted to the upper slide assembly 1334. The insert motor 1302 has a shaft (not shown) which is coupled to helical gear1 1308, which drives bevel gear2 1309, which is directly coupled to the drive shaft 1318. The drive shaft 1318 is rotatably mounted to a drive frame 1316. The drive shaft 1318 may be driven by the insert motor 1302, thereby turning the drive pulley (not shown), to actuate the serpentine belt 1312 in a forwards or reverse direction.

In the closed configuration of the elongate member manipulator 1300, as shown in FIGS. 91D and 91E, the idler belt assembly 1320 and the drive belt assembly 1310 may hold the guide wire 1060 with enough frictional force to propel the guide wire 1060 in the insert or retract directions when the insert motor 1302 is actuating the serpentine belt 1312. The multiple small idler belts 1322 will passively roll in the opposite rotational direction as the serpentine drive belt 1312.

The upper slide assembly 1334 may be actuated by a roll motor 1304 which causes the upper slide assembly 1334 to translate relative to the lower slide assembly 1330 to roll the guide wire 1060 held between the belt assemblies. The roll motor can drive a pinion which is coupled to racks on both the upper and lower slide assemblies 1334, 1330 to actuate the translational movement the slide assemblies as previously described Alternatively, any equivalent type of mechanism such as a leadscrew configuration could be used to actuate translation of the upper and lower slide assemblies. The elongate member support 1332 not only positions or holds the guide wire 1060 or other elongate member in the elongate member manipulator 1300 as previously described, but it also prevents the guide wire 1060 from buckling during guide wire insertion, retraction or roll actuation.

Other variations of the idler belt assembly 1320 could include any number of idler belts and pulleys, spaced apart by various distances which may allow for installation or positioning of the elongate member support 1332 between the belts. Accordingly the elongate member support 1332 could be provided with any number of support protrusions, spaced at any distance, and the drive belt assembly 1310 could be provided with any number of pulleys spaced apart at varying distances to provide for a plurality of windings. The idler belt assembly 1320 and drive belt assemblies 1310 can be configured to have mating belt segments such that the distances between each small idler belt 1322 is minimized to maximize belt contact with the guide wire 1060. The number of protrusions provided by the elongate member support 1332 could vary based on the diameter of the elongate member. For example, a greater number of protrusions and/or grooves may be provided for an elongate member having a smaller sized diameter which may require more support to prevent buckling of the elongate member.

Referring to FIGS. 95A-95C, an elongate member manipulator (not shown) can also include a valve holder 1350 which provides a mount for a valve assembly 1352 that encapsulates the elongate member (not shown). The valve holder 1350 may include an elongate member holder 1354 and a cover 1356. The valve holder 1350 can be mounted to an elongate member manipulator mounting bracket (not shown) with a screw 1358 and a knob 1360. A set of magnets (not shown) may be embedded in the cover 1356 and/or in the elongate member holder 1354 to provide a locking mechanism which holds the valve holder 1350 in a closed configuration. In other variations, different types of locking mechanisms such as, but not limited to clamps, latches, screws, etc., may alternatively be used. In one variation, the cover 1356, the elongate member holder 1354, and the knob 1360 could be made of a softer material such as a PET (poly ethylene terephthalate) thermoplastic while the screw 1358 could be made of stainless steel and the magnets could be made of neodymium. In alternative variations the materials could vary based on desired hardness of materials as well as costs.

If an operator desires to manually control the guide wire 1060 and decouple it from a robotic elongate member manipulator, such as manipulator 1300, the drive belt assembly 1310 can be pivoted open as illustrated in FIG. 15F, the valve holder 1350 can be opened, and the guide wire can be removed from the system along with the valve assembly 1352 and support tube 1056. The guide wire 1060 can then be rolled and inserted by hand in a manual manner which is well known in the art. The guide wire 1060 and valve assembly 1352 at any time can be quickly re-installed in the elongate member manipulator 1300 and robotic operation can continue seamlessly.

As shown in FIG. 96, both the drive belt assembly 1310 and idler belt assembly 1320 can be removeably replaceable to allow for installation of a sterile drape 1370 separating the sterile field portion of the elongate member manipulator from the non-sterile field portion of the elongate member manipulator (not shown). FIG. 96 illustrates the drive belt assembly 1310 and idler belt assembly 1320 being mounted using screw assemblies 1372. While similar captive screw mechanisms as previously described in reference to FIGS. 90A-C can be used, FIG. 96 illustrates an alternative variation. It should be understood that either variation shown in FIGS. 90A-C and the variation shown in FIG. 96 can be used for any elongate member manipulators described herein along with any other comparable type of mechanism which is well known in the art.

FIGS. 96A and 96B illustrate cross sectional top views of the drive belt assembly 1310 and idler belt assembly 1320. In one variation, the screw assemblies 1372 can be identical for the idler and drive belt assemblies or can vary in materials and dimensions if necessary to support different weights of each idler and drive belt assembly.

In an alternative variation, the drive belt assembly **1310** and idler belt assembly **1320** may need to be electrically isolated. Accordingly, the screw assembly **1372** can include a screw **1374**, a knob **1376**, an isolation cap **1378**, and an isolation sleeve **1380**. The screw **1374** can be made of stainless steel while the knob **1376** and isolation sleeve can be made of a thermoplastic, such as PET, and the isolation cap can be made of a thermoplastic, such as Ultem, providing for electric isolation. Alternatively, any other non-conductive material or thermoplastic can be used to manufacture the knob **1376**, isolation sleeve **1380**, and isolation cap **1378** or the drive frame **1316** and idler frame **1326** can be manufactured from a plastic or any other non-conductive material allowing for the screw assembly to be simplified and manufactured from stainless steel or any other type of metal.

The variation of elongate member manipulator **1300** shown in FIGS. **91**A-**91**F provides the idler belt assembly **1320** and elongate member support **1332** on the lower half of the manipulator **1300** while the drive belt assembly **1310** is provided on the upper half of the manipulator **1300** such that the drive belt assembly **1310** may pivot open to allow loading of a guide wire **1060**. In this variation, the insert motor **1302** may be mounted to the upper slide assembly **1334**. In an alternative variation, the drive belt assembly **1310** may be provided on the lower stationary half of the manipulator **1300** so the idler belt assembly **1320** with elongate member support **1332** could pivot for guide wire **1060** loading. In the latter variation, optionally, the insert motor **1302** may remain mounted to the stationary half of the manipulator **1300** which could be desirable.

FIGS. **96**C-**96**E illustrates a representation of an alternative elongate member manipulator **1700** which provides insert actuation using linear slide motion as opposed to feed rollers or feed belts as described in previous variations (see e.g., FIGS. **84**, **91**D, **99**, and **104**). FIG. **96**C illustrates a perspective view of the guide wire manipulator **1700** which can include a pad assembly **1702** mounted on a linear slide **1704** which The guide wire **1060** can be held between two pads of the pad assembly **1702**. To insert or retract the guide wire **1060**, the pad assembly **1702** can driven by a motorized leadscrew or motorized belt and pulley configuration (not shown) in the same manner which the guide splayer or sheath splayer is inserted as described in detail in the aforementioned incorporated references. FIGS. **96**D and E illustrate side views of the elongate member manipulator **1700** during roll actuation where the two pads of the pad assembly **1702** could be translated relative to one another to actuate roll of the guide wire **1060**. Sizing of the pads can vary as can pad material to provide the optimum frictional hold on the guide wire **1060** during roll and also during insert. Wire holders (not shown) can also be used to prevent slippage during roll. Insert and roll actuations can be completely independent motions actuated simultaneously or individually.

FIG. **97** illustrates another variation of an elongate member manipulator **1800** mounted to a variation of an instrument driver **1016**. The instrument driver includes a guide output plate **1053**, a sheath output plate **1043**. FIGS. **97*aa-ab*** illustrate different perspective views of the elongate member manipulator **1800** shown without a cover **1801** for clarity. The elongate member manipulator **1800** can be fixably mounted to a manipulator mounting bracket **1858** which in turn can be fixably mounted to the guide output plate **1053**.

FIGS. **97A1** and **97A3** illustrate different perspective views of the elongate member manipulator **1800** in a closed configuration while FIGS. **97A2** and **97A4** illustrate the elongate member manipulator in an open configuration. The elongate member manipulator **1800** includes the cover **1801**, a drive belt assembly **1810**, an idler belt assembly **1820**, and an elongate member support **1860**. The cover **1801** is configured in three sections such that a middle section may hinge open to allow the elongate member manipulator to open for loading and unloading of a guide wire **1060** and valve assembly **1352** into and out of the elongate member support **1860**. The elongate member manipulator **1800** can be locked in a closed configuration by securing a locking knob **1813** into a locking knob threaded hole **1815**.

FIGS. **97**B**1**-B**2** illustrate different perspective views of the elongate member manipulator **1800** with the cover **1801** removed. Several components including but not limited to the drive belt assembly **1810**, the idler belt assembly **1820**, an upper slide assembly **1834**, a lower slide assembly **1830**, an insert motor **1802**, a roll motor **1804**, and the elongate member support **1860** are structurally and functionally similar to corresponding components of the elongate member manipulators **1200**, **1300** of FIGS. **9**B and **15**D-F previously described. Referring to FIG. **97**B2 both the roll and insert mechanism can be seen. FIG. **97**B3 illustrates a zoomed in view of the roll motor and accompanying mechanisms with the manipulator mounting bracket (**1858** shown in FIG. **97**B2) hidden for clarity. The roll motor **1804** directly drives a roll drive shaft **1806** which is coupled to a roll belt **1808** which in turn drives a pinion **1838**. As previously described in detail, the pinion **1838** drives a rack which controls linear movement of the upper slide assembly **1834** relative to the lower slide assembly **1830** along linear bearings **1836**. The belt drive assembly provides increased torque when actuating the upper slide assembly **1834**. The drive belt assembly **1810** can be fixably coupled to the upper drive assembly **1834** while the idler belt assembly **1820** can be fixably coupled to the lower drive assembly **1830**. Thus linear movement between the drive and idler belt assemblies **1810**, **1820** provide for roll of a guide wire held between the belt assemblies **1834**, **1820**. Foot supports **1812** may be provided to provide cantilever support of the belt assemblies **1810**, **1820** as they are mounted to the upper and lower slide assemblies respectively **1834**, **1830**. The upper slide assembly **1834** may then be locked to the lower slide assembly **1830** in a closed configuration using the locking knob **1813** which threads into the lower slide assembly **1830**.

FIG. **97**C illustrates the insert motor **1802** mounted to the upper slide assembly **1834** with the drive belt assembly **1810** installed. Other components of the guide wire manipulator **1800** are hidden for clarity. The insert motor **1802** drives a set of helical gears **1803** that actuate an insert shaft **1814**. When the drive belt assembly **1810** is coupled to the upper slide assembly **1834**, a drive shaft (not shown) is engaged with the insert shaft **1814**. As the insert shaft **1814** is actuated by the insert motor **1802**, the drive shaft actuates a drive belt **1818** in a manner previously described in detail for the elongate member manipulator **1300** shown in FIGS. **15**A-D. The drive shaft **1816** can be seen in FIGS. **97**D**1**-D**3**. FIG. **97**D**1** illustrates a perspective view of the drive belt assembly **1810**, FIG. **97**D**2** illustrates a cross sectional bottom view of the drive belt assembly **1810**, and FIG. **97**D**3** illustrates a zoomed in view of the end of the drive shaft **1816** which is coupled to the upper slide assembly **1834**. A drape which will be described in detail below can be installed between the drive and idler belt assemblies **1810**, **1820** and the upper and lower slide assemblies **1834**, **1830** respectively. The drape will provide a sterile barrier between the mechanisms of the elongate member manipulator **1800** and the belt assemblies **1810**, **1820**. In some situations fluids, for example blood, saline, or water may flow onto the drape. In order to prevent fluid ingress into the mechanisms of the elongate member manipulator through particularly the insert shaft **1814** shown in FIG. **97**C,**21**C, a labyrinth seal **1817** may be provided. The labyrinth shape of the drive shaft **1816** as shown in FIG. **97**D**3** in conjunction with the labyrinth seal creates a winding path which fluid would need to pass through before leaking into the insert shaft **1814**. Additionally, the drive shaft **1816** rests within a hole **1819** in the foot support **1812** which may be configured with a ring groove **1819** which can direct fluid away or downwards prior to entering the labyrinth seal **1817**.

In one variation, to accurately grip the guide wire between the belt assemblies **1810**, **1820**, the belt assemblies are configured such that they are predominantly parallel with respect to one another. An adjustment mechanism that provides for alignment of the drive belt assembly to the idler belt assembly is described with reference to FIGS. **97**E**1**-G. FIGS. **97**E**1**-E**2** illustrates the elongate member manipulator **1800** with several components hidden for clarity showing the upper and lower slide assemblies **1834**, **1830** fixably coupled to the drive and idler belt assemblies (**1810**,**1810**, **1820**) respectively. The drive belt assembly **1810** can be fixably coupled to the upper drive assembly **1834** while the idler belt assembly **1820** can be fixably coupled to the lower drive assembly **1830** using screw assemblies **1822** which are configured to thread into belt assembly mounting holes **1824**. Thus adjustment of the upper slide assembly **1834** relative to the lower slide assembly **1830** will result in corresponding adjustment of the drive belt assembly **1810** with respect to the idler belt assembly **1820**. While the lower slide assembly **1830** can be mounted stationary to the manipulator mounting bracket **1858** without adjustments, the upper slide assembly may be configured with adjustment mechanisms which will now be described.

FIG. **97**F illustrates a partially exploded view of the elongate member manipulator (**800**) **1800** of FIG. **97**E with the drive and idler belt assemblies hidden for clarity. The upper slide assembly **1834** can include a top plate **1840** and a bottom plate **1842**. The top plate **1840** which includes an alignment bar **1844** centered in a top plate opening **1841**, an adjustment set screw **1847**, an adjustment nut screw **1848** and an adjustment spring **1850** is illustrated exploded from the bottom plate **1842** which includes a cradle **1846**. When assembled, the cradle is configured to hold the alignment bar **1844** in a manner that allows the alignment bar **1844** to float in three separate axes of motion. FIG. **97**G illustrates a simplified representation of the alignment bar **1844** held within the cradle **1846** showing top, front and side views. The alignment bar **1844** can rotate about its own axis as shown with roll arrow **1852**, translate up and down as shown with vertical arrow **1854**, and also rotate in a rocking motion as shown with pitch arrow **1856**. The alignment bar **1844** is constrained in this configuration from rotating in a yaw motion or translating in a side to side direction. It is also constrained by the fit of the cradle **1846** to the top slide plate opening **1841**.

In this configuration, because the drive belt assembly **1810** is fixably mounted to the top plate **1840**, as the top plate **1840** floats in a roll, vertical, or pitch direction, the drive belt assembly **1810** and top plate **1840** float as a single component. The adjustment set screw **1847** can be tightened or loosened to set the overall height of the top plate **1840** and drive belt assembly **1810** relative to the idler belt assembly **1820**. The adjustment not screw **1848** is tightened down increasing the downward force provided by the adjustment spring **1850** which presses the belt assemblies together. The adjustment set screw **1847** acts as a reaction or pivot point allowing the top plate **1840** to gimble about the roll and pitch axes of the alignment bar **1844**. As the drive belt assembly **1810** comes in contact with the idler belt assembly **1820**, the latter of which is stationary, the alignment bar **1844** provides the capability of self parallel alignment between the two belt assemblies. The alignment nut is tightened completely to secure the top plate **1840** to the bottom plate **1842** such that the position of the drive belt assembly **1810** is securely set.

FIGS. **97**H**1**-H**2** illustrate the elongate member manipulator **1800** with the drive belt assembly and idler belt assembly removed showing the elongate member support **1860** mounted to the manipulator mounting bracket **1858** using a pair of mounting set screws **1866** which thread into member support mounting holes **1859**. FIG. **97**J**1** illustrates the elongate member support **1860** with the valve assembly **1352** and guide wire **1060** installed. The elongate member support **1860** includes a support body **1862** and a valve holder **1864** which can be securably fixed to the support body **1862** using screws **1863**. FIG. **97**J**2** illustrates the elongate member support **1860** in an open configuration allowing the valve assembly **1352** and guide wire **1060** to be removed. The valve assembly **1352** and guide wire **1060** can be coupled as an assembly and can be removed and replaced into the elongate member manipulator **1800** with opening of the valve holder **1864** and the opening of the drive belt assembly **1810** which hinges open as previously described. FIG. **97**J**3** illustrates the valve holder **1864** in a closed configuration including a set of magnets **1870** are in the top and bottom portions of the valve holder **1864** which lock the valve holder **1864** in a closed position. A stop **1869** can be provided to prevent the valve holder **1864** from opening beyond a set rotation to prevent collision with any other components of the elongate member manipulator **1800** or any other tools or instruments used during a surgical procedure. Magnets **1872** embedded in the stop and top portion of the valve holder **1864** lock the valve holder **1864** in an open position as shown in FIG. **97**J**4**.

FIG. **97**K**1** illustrates a variation of a drape assembly **1900** that may be used to cover the elongate member manipulator and instrument driver. As previously described, the drape assembly can be used to create a sterile barrier between the instrument driver and non-sterile portions of the elongate member manipulator with the drive belt assembly, idler belt assembly, and guide wire. The drape assembly allows transfer of mechanical motion from the instrument driver to each splayer as well as from the motors of the elongate member manipulator to the drive and idler belt assemblies. FIG. **97**K**2** illustrates a zoomed in view of the drape assembly **1900** which can include a drape body **1901**, sheath foam pad **1902**, a leader foam pad **1904**, a tenting frame **1920**, drape member support holes **1936**, and a locking knob hole **1938**. The drape member support holes **1936** and locking knob hole **1938** can be reinforced with frames that will provide additional strength to prevent tearing of the drape when screws are installed through the holes. The sheath and leader foam pads **1902**, **1902** were described previously in detail.

Referring to FIGS. **97**L**1**-L**2**, the tenting frame **1920** is illustrated from top and bottom perspective views respectively showing flexure bases **1922**, flexures **1924**, adhesive portions **1926**, and reinforcement members **1928**. Each flexure base **1922** of the tenting frame **1920** can be fixable attached to the drape body **1901** with adhesive. The flexures **1924** of the tenting frame **1920** can adhere to the drape body **1901** along adhesive portions **1926** of each flexure **1924** positioned along the centerline of the tenting frame **1920**. The remaining length of each flexure **1924** can be free to move relative to the drape body **1901**. The reinforcement members **1928** can include drape idler belt mounting holes **1934**, drape drive belt mounting holes **1930** and a drape drive shaft hole **1932**. The reinforcement members **1928** are provided to reinforce the mounting holes **1930**, **1934**. The reinforcement members **1928** can be made from a material which is tough enough to provide some strength where high forces will be imposed while also providing flexibility. Also it can be desirable for the reinforcement members **1928** to remain as thin as possible. If the reinforcement member **1928** are thick and compressible, as mounting screws are tightened down the material is compressed. As the material settles in the screws may require re-tightening which can be undesirable for mid-procedure work flow. The reinforcement members **1928** can be made from polycarbonate or any other type of plastic which fulfills the stiffness, thickness, and material strength requirements. Materials for other components can include but not be limited to polyethelene for the drape body **1901** and high-density polyethylene (HDPE) for the tenting frame flexure base **1922**, flexures **1924**, and reinforcement frames for the drape drive shaft holes **1932**, drape idler mounting holes **1934**, drape member support holes **1936**, and drape locking knob hole **1938**.

FIG. **97M1** illustrates a simplified model of the elongate member manipulator **1800**. For clarity, only the model of the elongate member manipulator **1800** and drape assembly **1900** are being shown. It should be understood that the elongate member manipulator **1800** may be installed on the previously described instrument driver (**1016** of FIG. **15**A) and the drape assembly **1900** can be configured to surround both the instrument driver and elongate member manipulator **1800**. In order to install the drape assembly **1900** to the elongate member manipulator **1800**, the sterile components including the drive and idler belt assemblies, the elongate member support (**1810**, **1820**, and **1860** respectively), and the locking knob **1813** are removed from the elongate member manipulator **1800** as shown in FIG. **97M1**.

Referring back to FIGS. **97**A**2**, **97**H**2**, **97**K**2**, **97**L**1**, **97**E**2** and to FIGS. **97M2-M5**, one variation of a method of installing a drape onto an elongate member manipulator **1800** can be seen. In this variation, the drape member support holes **1936** are aligned with the member support mounting holes **1859** and the elongate member support **1860** can be installed by securing the mounting set screws **1866** into the member support mounting holes **1859** as shown in FIG. **97M2**. The drape idler belt mounting holes **1934** are aligned with the idler belt mounting holes **1824** and the idler belt assembly **1820** is installed to the lower slide assembly **1830** by securing the idler screw assemblies **1822** into the idler belt mounting holes **1824** as shown in FIG. **97M3**. The tenting frame **1920** is folded over such that the drape drive belt mounting holes **1930** can be similarly aligned with the drive belt assembly mounting holes **1825** and the drive belt assembly **1810** can be installed by securing the drive screw assemblies **1823** into the drive belt assembly mounting holes **1825** in the upper slide assembly **1834** as shown in FIG. **97M4**. The locking knob **1813** is then fit through the drape locking knob hole **1938** and secured into the locking knob thread hole **1815**. The drape is held securely in place between the sterile components including the elongate member support **1860**, the idler and drive belt assemblies **1820**, **1810**, and locking knob **1813** providing a sterile barrier between the sterile components and the non-sterile components of the elongate member manipulator **1800** and instrument driver.

During use, the locking knob **1813** can be loosened while being held captive such that the elongate member manipulator **1800** can be opened in order to load a guide wire **1060** as shown in FIG. **97A1-A2.21A1-A2**. The tenting frame **1920** is unfolded and stretched allowing the elongate member manipulator to open while continuing to cover the non-sterile components of the elongate member manipulator **1800**. The guide wire **1060** and valve assembly **1352** can then be loaded and the elongate member manipulator **1800** can be closed for use including the rolling of the guide wire **1060** by translation of the upper and lower slide assemblies **1834**, **1830** as previously described. The tenting frame **1920** can serve multiple functions. It pushes the drape body **1901** in an outward direction so that the drape body **1901** is not pinched between the upper and lower slide assemblies **1834**, **1830** as they are opened and closed. Also because the upper and lower slide assemblies **1834**, **1830** translate relative to each other during use, excess drape material must be provided so that the drape body **1901** doesn't tear with this movement. Because the tenting frame **1920** is secured to the drape body **1901** only along its centerline along the adhesive portions **1926**, the tenting frame **1920** shapes the drape body **1901** to manage the excess drape material.

FIGS. **98**A-**98**B illustrate a different variation of an elongate member manipulator **1400** mounted on the instrument driver **1016** using a manipulator mounting bracket **1058** such that a guide wire (not shown) can be fed into the valve assembly **1352**, then into the support tube **1056** which subsequently feeds into a guide splayer **1052** or sheath splayer. In alternative variations, the elongate member manipulator **1400** could be mounted on the instrument driver **1016** with a guide and/or a sheath splayer assembly (e.g., the assembly **50**/**40** in FIG. **2**), the elongate member manipulator could be mounted with just a sheath assembly **1040** or the elongate member manipulator **1400** could be mounted alone.

FIG. **99** illustrates the elongate member manipulator **1400** mounted to the manipulator mounting bracket **1058** with a guide wire **1060** loaded therein. FIGS. **100**A-**100**B illustrates the elongate member manipulator **1400** without a motor pack cover **1401** showing an insert motor **1402**, a roll motor **1404** and a belt assembly **1410**. FIGS. **101**A-**101**C illustrate a front and rear perspective view as well as a end view of the belt assembly **1410** which includes a drive belt **1412**, an idler belt **1422**, a drive pulley **1414**, idler pulleys **1424**, bevel gears **1416**, a driving gear **1418**, an idler gear **1426**, a driven gear **1420**, and a clamp assembly **1440**. The belt assembly **1410** can be removably replaceable such that a sterile drape can be inserted between the belt assembly **1410** and the remaining drive components, such that the belt assembly **1410** may be positioned in a sterile field with the guide wire **1060**.

To aid in loading the guide wire **1060** into the belt assembly **1410**, the clamp assembly **1440** may be provided to open and close the belt assembly **1410** as shown in FIGS. **102**A and **102**B. FIGS. **102**A-**102**B each illustrate a side view of the drive assembly **1410** where FIG. **102**A shows the belt drive assembly in a closed configuration while FIG. **102**B shows the belt drive assembly in an open configuration. As seen best in FIGS. **101**B-**101**C, the clamp assembly **1326** includes a clamp **1442** that levers about a pivot **1444** to open and close the idler belt **1412** portion of the belt drive assembly in a clamping motion. A pair of clamp springs **1446** can be used to provide the clamping force for closing the clamp assembly in a nominally closed position. The clamp springs **1446** can be sized to provide for enough clamp force to hold the drive and idler belts **1412**, **1422** together and effectively pinch the guide wire **1060** so it can be secured between the drive and idler belts **1412**, **1422** while preventing damage to the guide wire **1060**. To load the guide wire **1060**, the clamp **1442** can be manually opened by compressing the springs **1446** while the guide wire may be back loaded through the belt drive assembly.

In order to actuate the belt assembly **1410**, FIG. **100**B and to FIG. **101**B show the insert motor **1402** driving an insert belt **1406**, turning an insert shaft **1428**, turning the driving gear **1418**, the idler gear **1426** and ultimately the driven gear **1420** which is coupled to a shaft driving the bevel gears **1416**. The idler belt **1422** is free to rotate around the passive idler pulleys **1424**. As seen in FIG. **101**A, the bevel gears drive the drive pulley **1414** which turns the drive belt **1412** over idler pulleys **1424**. The drive belt **1412** and the idler belt **1422** are pressed together causing the idler belt **1422** to rotate in the opposite direction as the drive belt **1412** and thus driving the guide wire **1060** pinched between both belts in the insert or retract direction depending on the direction of the drive belt actuation. Referring back to FIG. **100**B, roll actuation of the guide wire **1060** is illustrated. In order to roll the guide wire **1060** the entire belt assembly **1410** is rolled on a roll shaft **1430**. The roll shaft **1430** is coupled to a roll belt **1408** driven by the roll motor **1404**.

FIG. **103** illustrates another variation of an elongate member manipulator **1500** coupled to the instrument driver **1016** via a mounting bracket **1058** positioned such that a guide wire (not shown) could feed through the elongate member manipulator **1500** and into a guide catheter splayer **1202** and/or sheath splayer. In alternative variations, the elongate member manipulator **1500** could be mounted on the instrument driver **1016** with a guide and/or a sheath splayer assembly (e.g., assembly **50**/**40** in FIG. **2**), the elongate member manipulator could be mounted with just a sheath assembly **1040**, or the elongate member manipulator **1400** could be mounted alone.

FIG. **104** shows the elongate member manipulator **1500** with its cover removed, mounted to a manipulator base **1570** which in turn is mounted to the manipulator mounting bracket **1058**. The elongate member manipulator **1500** includes an insert motor **1502**, insert belt **1506**, feed roller assembly **1510**, roll motor **1504**, and roll belt **1508**. The insert motor **1502** and roll motor **1504** are each fixably mounted to the manipulator base **1570** and are coupled to an insert shaft **1528** and roll shaft **1530** respectively.

FIG. **105** illustrates the feed roller assembly **1510** which includes the roll shaft **1530** and the insert shaft **1528**. The insert motor **1502** drives the insert belt **1506**, which rotates the insert shaft **1528** coupled to a drive gear **1518**, which drives a driven gear **1520** which is coupled to bevel gears **1516**, ultimately rotating a drive feed roller **1512**, which can be positioned adjacent to an insert feed roller **1522**. In one variation, the insert feed roller **1522** could be passive such that when the drive feed roller **1512** is actuated in one rotational direction, the frictional force between the drive feed roller **1512** and insert feed roller **1522** causes the insert feed roller to rotate in the opposite rotational direction. A guide wire (not shown) can be positioned between the drive feed roller **1512** and insert feed roller **1522** such that rotation of the feed rollers would result in a propelling actuation of the guide wire in the insert or retract directions depending on the rotational direction of the feed rollers.

An alternative variation for actuation of the feed rollers is illustrated in FIG. **106**A which is a zoomed in view of the feed roller assembly **1510** with certain components hidden or shown as transparent for clarity. FIG. **106**B is a top view of FIG. **106**A. In this variation, the insert feed roller **1522** is not passive but is driven at the same rate as drive feed roller **1512** in an opposite rotational direction thereby inserting or retracting the guide wire **1060** held between the feed rollers.

FIG. **107**A illustrates a top view of the feed roller assembly **1510** while FIG. **107**B illustrates a bottom view where certain components are shown as transparent for clarity. In this figure a feed roller gear train can be seen which includes four gears with identical gear ratios including a drive gear **1514**, a first idler gear **1515**, a second idler gear **1517** and a driven gear **1519**. By way of example but not limitation, each gear could be sized with a 48 pitch and 27 tooth count which could be coupled to feed rollers that are ⅝" in diameter. In alternative variations, the gears could be sized with varying pitch and tooth count and the feed roller may have varying diameters.

Drive gear **1514** is coupled to drive feed roller **1512** such that rotary motion of drive feed roller **1512** actuates drive gear **1514** in a one-to-one rotary motion. Drive gear **1514** rotates first idler gear **1515** which rotates second idler gear **1517**, rotating driven gear **1519** which is coupled to driven feed roller **1522** such that rotation of driven gear **1519** actuates insert feed roller **1522** in a one-to-one rotary motion. Thus rotation of the drive feed roller **1512** via the gears, belts and motors previously described rotates insert feed roller **1522** at the same rate in an opposite rotational direction. By way of example, when drive feed roller **1512** is rotated in the clockwise direction, drive gear **1514** is also rotated at the same rate in the clockwise direction. Drive gear **1514** then drives first idler gear **1515** in the counterclockwise direction, which drives second idler gear **1517** in the clockwise direction, which drives driven gear **1519** in the counterclockwise direction all at the same rotational rate if all gears have identical gear ratios. Driven gear **1519** coupled to the idler feed roller **1414** rotates idler feed roller in the counterclockwise direction resulting in opposite rotation of the drive feed roller **1512** and the driven feed roller **1522**.

Roll of the guide wire may be actuated by rolling the feed roller assembly **1510**. Referring back to FIG. **104**, the roll motor **1504** is illustrated actuating the roll belt **1508** which in turn rotates the roll shaft **1530** rolling a feed roller assembly **1510** and ultimately rolling the guide wire (not shown) being held tightly between the feed rollers **1512**, **1522**.

With elongate member manipulators **1400** and **1500**, the insert belt **1406**, **1506** and roll belt **1408**, **1508** are coupled to shafts **1428**, **1528**, **1430**, **1530** which are rotatably coupled to bearings so they are free to rotate independently about the same axis of rotation. However, if either the belt assembly **1410** or feed roller assembly **1510** is actuated to roll but the insert belt **1406**, **1506** remains stationary, the drive belt **1412** or drive feed rollers **1512** will not remain stationary. Using the elongate member manipulator **1400** from FIG. **100**B as an example, if the belt assembly **1410** rolls by actuating the roll motor **1404** and the insert motor **1402** remains off, the driving gear **1418** remains stationary while the idler gear **1426** circumvents the driving gear **1418** with the motion of the roll assembly **1402**. Thus, the rotation of the idler gear **1426** results in rotation of the driven gear **1420** and subsequent rotation of the bevel gears **1416** causing rotation of the drive belt **1412** and undesired insert of the guide wire **1060**. The actuation of the insert motor may match the actuation of the roll motor such that as the idler gear **1426** circumvents driving gear **1418** without rotating about its own axis. The rotation of the insert motor **1402** and roll motor **1404** may be coordinated to achieve the desired actuation.

In order to actuate the guide wire in the feed/insert/retract direction only, the insert motor would be actuated while the roll motor would remain off. In order to roll the guide wire only without insertion/retraction, the roll motor is turned and the insert motor is turned at an identical rate. In order to feed and roll the guide wire simultaneously, the insert and roll motors may be actuated at different rates. Because the current variation actuates roll by rolling the entire structure, roll and insert of the guide wire can be simultaneously actuated without the effect of stripping or winding up the guide wire. The guide wire does not have to overcome any frictional holding effects at the feed belts when being actuated in a roll direction since the feed belts themselves are being rolled.

FIGS. **106**A-**107**B show an example of a spring mechanism **1556** that can provide for a constant force applied to the guide wire (not shown) by the feed rollers **1512**, **1522**. The spring mechanism **1556** can provide for the ability to grip variously sized guide wire diameters, and it can also allow for top loading of the guide wire into the feed roller assembly **1510**. The spring mechanism **1556** can include a frame **1552**, a pivot frame **1554**, a spring mount **1558**, and a spring **1560**. The frame **1552** is shown in FIG. **106**A as a solid case surrounding second idler gear **1517**, first idler gear **1515**, and drive gear **1514**. The frame **1552** remains stationary relative to the insert shaft **1528** such that the only movement experienced by the frame **1552** is rotation during roll of the feed roller assembly **1510**. The pivot frame **1554** is shown as a transparent case fit into the frame **1552** but surrounding driven gear **1519**, second idler gear **1517** and the spring **1560** in a cup **1562**. The spring mount **1558** is shown as a solid flange which holds one end of the spring **1560** in place constraining it within the cup **1562**. The spring mount **1558** may be attached to the main plate **1452** using a pair of screws **1564**, so that it is stationary to the frame **1552** (as best shown in FIG. **31**B). The pivot frame **1554** is mounted such that it can rotate about second idler gear **1517** but due to the spring force the pivot ram **1554** is held in a nominally closed position pinching the feed rollers **1512**, **1522** together. The spring **1560** can be sized to optimize the force necessary to hold a guide wire with enough friction to actuate it in the insert and roll directions while not damaging the guide wire. By way of example but not limitation, the pivot plate can be sized so that a swing arm allows a 2 to 1 pinch advantage between feed rollers such that a 2.5 lb spring would result in a 5 lb pinch force at the feed rollers. With a 2.5 lb spring, the range of guide wire diameters could be between about 0.014" and 0.038." In this example, a wire diameter smaller than about 0.014" may not be gripped adequately to provide insert and roll motion without slipping and a wire diameter above about 0.038" may be damaged by the pinch force.

In one variation, the guide wire **1060** can be back loaded into the elongate member manipulator by manually loading the guide wire **1060** into the proximal end of the feed roller assembly **1510**, loading it into the proximal end of the roll shaft **1532** which could be provided with a thru lumen, and actuating the insert motor **1502** to actuate the feed rollers **512**, **522** in the insert direction until the desired length guide wire **1060** is fed through the elongate member manipulator **1500**. In an alternative variation, the guide wire **1060** can be back loaded into the roll shaft **1530** as described above but then top loaded into the feed roller assembly **1510**. To top load the guide wire **1060** the spring **1560** could be compressed by manually squeezing the pivot frame **1554** towards the cup **1562** on the frame plate **1552**, pivoting both the pivot plate **1554** and idler feed roller **1522**. FIGS. **108**A and **1088** show a representation of the bottom view of the gear train and feed rollers, and illustrate the spacing between the drive feed roller **1512** and the idler feed roller **1522** created by squeezing the spring **1560** and pivot frame **1554**. The guide wire can then be loaded from above into a groove **1566** shown in FIGS. **106**A, **106**B, and **107**A which helps center the guide wire between the feed rollers **1512**, **1522**.

FIG. **109** illustrates a variation of a feed roller configuration that may prevent or reduce slippage of the guide wire **1060** between the drive feed roller **1512** and the insert feed roller **1522** when insert or roll motion is actuated. In this variation, the drive feed roller **1512** is configured with a V-groove **1568** cut around its diameter. The guide wire **1060** may fit in the V-groove **1568** and be held in position by the insert feed roller **1522**. The guide wire **1060** may be held by three points of contact, two within the V-groove **1568** and one with the drive feed roller **1512** without a groove thus constraining the guide wire **1060** vertically and rotationally. In alternative variations, a similar groove may be cut into the drive feed roller **1512** or it may be cut in the drive feed roller **1512** and not the insert feed roller **1522**. The groove may be of various dimensions depending on the range of wire diameter sizes and the necessary contact between the groove and the guide wire. The groove may also be of various shapes including but not limited to semi-circular, square, or any polygon shape which could provide for necessary contact with the guide wire.

Referring back to FIG. **107**A, a guide wire groove **1566** is provided to help align the guide wire (not shown) vertically with the V-groove **1568** in the drive feed roller **1412** as well as center the guide wire in between both feed rollers **1512**, **1522**.

As previously described, it can be desirable to maintain the guide wire **1060** and a minimal number of disposable components in a sterile field and the remaining components in a non-sterile field. As shown in FIGS. **110**A-**110**B, in one variation, the feed roller assembly **1510** could be separated into two sub-assemblies, an insert assembly **1511** which is maintained in the sterile field and an actuation assembly **1513** positioned in the non sterile field. The insert assembly **1511** could include the gears and rollers provided for insertion of the guide wire including but not limited to the spring mechanism **1556**, gears (**1514**, **1515**, **1517**, **1519**), rollers **1512**, **1522**, driven gear **1520**, and bevel gears **1516**.

The actuation assembly **1513** could include the driving gear **1518**, insert shaft **1528**, and roll shaft **1530**. While the actuation assembly **1513** still includes a number of gears and pulleys, a number of expensive components including gears, the insert and roll motors **1502**, **1504**, insert and roll belts **1506**, **1508**, and instrument driver **1016** would remain in the non-sterile field.

FIGS. **109**-**110** also show one way to mount the insert assembly **1511** to the actuation assembly **1513** allowing for separation of sterile versus non-sterile components where the insert assembly **1511** could be removeably coupled to the actuation assembly **1513** which is fixably mounted to the other components of the elongate member manipulator **1500**. A sterile drape (not shown) could be positioned between the insert assembly **1511** and the non-sterile components. Referring to FIG. **110** as well as back to FIG. **108**, the insert assembly **1511** could be mounted to a mounting plate **1572** using mounting screws **1574**. The mounting plate **1570** could be fixably mounted to a manipulator base **1570** which provides the base structure for the insert motor **1502**, the roll motor **1504** and the feed roller assembly **1510**. In alternative variations, an interface that allows for quick removal and replacement of the insert assembly **1511** without the use of tools could be used. Additionally the interface could include mating components on the sterile drape.

It should be understood that any of the previously described elongate member manipulators could include multiple variations of feed roller and/or feed belt combinations. FIGS. **111**A-**111**D illustrate examples of such combinations. FIG. **111**A illustrates a variation using multiple feed roller pairs **1710**, **1712***a*, **1712***b*, **1712***c* for actuating the guide wire **1060** where motor driven feed roller pair **1710** drives the guide wire **1060** in an insert motion while feed roller pairs **1712***a*, **1712***b*, **1712***c* can be idler rollers which are free to rotate. FIG. **111**B illustrates a variation using multiple feed belt pairs **1720**, **1722***a*, **1722***b* for actuating the guide wire **1060** in an insert motion where feed belt pair **1720** is motor driven and feed belt pairs **1722***a*, **1722***b* are idler belts which are free to rotate. FIG. **111**C illustrates a variation that uses a combination of feed roller pairs and feed belt pairs where feed roller pair **1714** is motor driven while feed roller pair **1716** and feed belt pairs **1724***a*, **1724***b* are idle and free to rotate. Alternatively feed belt pair **1724***a* can be motor actuated while feed belt pair **1724***b* and feed roller pairs **1714**, **1716** are idle as shown in FIG. **111**D. FIGS. **111**E and **111**F illustrate alternative variations which feed rollers and feed belts are not used in pairs but a single set of feed rollers **1718***a*, **1718***b*, **1718***c* and a feed belt **1726** are used to grip the guide wire **1060**. FIG. **111**E illustrates a variation in which the feed roller **1718***a* is motor driven to actuate the guide wire **1060** while FIG. **111**F illustrates the feed belt **1726** as motor driven.

It should be understood that alternatively any of the idle roller pairs and idle belt pairs could be motor driven, any motor driven feed roller pairs and feed belt pairs could be idle, and while a specific number of pairs of rollers and/or belts are illustrated, any number can be used. Additionally in any pair of feed rollers or feed belts, one feed roller or feed belt could be motor driven while the other could be idle. In the configuration illustrated in FIGS. **111**C and **111**D, any combination of feed roller pairs and feed belt pairs could be used in any order and furthermore any combination of feed rollers, feed roller pairs, feed belts and feed belt pairs from any of the variations previously described may be used. Motor driven actuation can be provided in the manner previously described and roll actuation of the guide wire can be provided with the translation of the feed rollers/feed belts along their own axes of rotation also previously described.

FIGS. **124**A-C illustrate another alternative variation of an elongate member manipulator **1600**. FIG. **124**A illustrates the elongate member manipulator **1600** with a manipulator cover **1601** installed while FIG. **124**B illustrates the manipulator cover **1601** removed. The elongate member manipulator **1600** includes a member holder **1608**, an insertion drive **1610**, and a rotation drive **1620** each of which can be directly or indirectly mounted to a manipulator base **1606**. FIG. **124**C shows the insertion drive **1610** which includes an insert motor **1602**, a leadscrew **1612**, a leadscrew nut **1614**, and/or a linear slide **1616**.

FIGS. **125**A-C illustrate a perspective, side, and zoomed in views of the rotation drive **1620** respectively which includes a rotation base **1618**, a rotation drive bracket **1622**, roll motor **1604**, a drive gear **1624**, a rotation gear **1626**, a collet **1628**, a collet solenoid **1632**, and/or a collet mount **1634**. The collet **1628** can be coupled to the collet mount **1634** using collet bearings **1636** such that the collet **1628** can be free to rotate within the collet mount **1634**. The collet **1628** may also be coupled or fixably coupled to the rotation gear **1626** such that actuation of the rotation gear **1626** would drive rotation of the collet **1628**.

FIG. **125**B illustrates the rotational drive **1620** with the guide wire **1060** loaded. It should be understood as described previously that the guide wire **1060** is shown for illustrative purposes and any type of elongate member may be loaded into the manipulator **1600**. In order to load the guide wire **1060** into the system, the collet **1628** can be opened, the guide wire **1060** can be backloaded into the system, and the collet **1628** can then be closed gripping the guide wire **1060**. The collet **1628** functions as a typical chuck or collet chuck as is well known in the art such that in order to loosen or tighten the collet **1628**, one end of the collet **1628** would be held stationary while the other end is rotated. Depending on the direction of rotation, the collet is either tightened around the guide wire **1060** or loosened from the guide wire **1060**. In this variation, the opening and closing of the collet **1628** can be automatically or remotely controlled. The collet **1628** can be geared such that collet teeth **1630** can mate with the collet solenoid **1632**. When the collet solenoid **1632** is activated to engage one end of the collet **1628** is held stationary, the roll motor **1604** can turn the drive gear **1624**, which will rotate the rotation gear **1626**, rotating the other end of the collet **1628** which will loosen or tighten the collet **1628** depending on the direction of rotation.

Once the collet **1628** is closed adequately holding the guide wire **1060**, the collet solenoid **1632** can be disengaged from the collet teeth **1630**. In this configuration, rotation of the rotation gear **1626** which is indirectly driven by the roll motor **1604** will not cause the collet **1628** to loosen or tighten. Instead, the entire collet **1628** will rotate with the rotation gear **1626** thus rolling the guide wire **1060** which is held securely in the collet **1628**.

In order to actuate the guide wire **1060** in the propelling motion, inserting or retracting it axially, the rotation drive **1620** can be mounted to linear slide **1616** as shown in FIG. **124**C. The leadscrew nut **1614** can be fixably mounted to the rotation base **1618** and coupled to the leadscrew **1612** such that when the insert motor **1602** drives the leadscrew **1612**, rotation drive **1620** is controllably driven linearly and the guide wire **1060** can be controllably propelled in the insert or retract direction depending on the rotational direction of the insert motor **1602**.

In one variation, the insert/retract stroke can be limited by the physical travel of the linear slide **1616**. In an alternative variation, an infinite insert or retract distance may be achieved.

FIG. **126** shows a side cross sectional view of the elongate member manipulator **1600** illustrating the member holder **1608** which can include a holder solenoid **1638**. The holder solenoid **1638** can include a holder tip **1640** that is actuated to hold or release the guide wire **1060**. When the guide wire **1060** is being actuated in the roll or propelling directions, the holder solenoid **1638** can be actuated to release the guide wire **1060** to move freely through the member holder **1608**. When the linear slide **1616** has reached its forward limit in the propelling direction, the holder solenoid **1638** can be actuated to hold the guide wire **1060** in the member holder **1608**, the collet **1628** can be actuated to open, releasing its grip on the guide wire **1060**, and the rotational drive **1620** can be translated back to the reverse limit of the linear slide **1616**. The collet **1628** can then be actuated to tighten around the guide wire **1060**, the holder solenoid **1638** can be actuated to release the guide wire **1060** within the holder member **1608**, and the guide wire **1060** can again be actuated in the propelling and roll directions in the manner previously described. The same method can be used in the retract direction.

In one variation, algorithms for control of the elongate member manipulator **1600** can be applied such that the sequence of collet and holder solenoids **1632**, **1638** as well as insert and roll motors **1602**, **1604** are coordinated to create rapid and seamless actuation of the elongate member manipulator **1600**. Additionally algorithms can be implemented that will control the opening and closing of the collet **1628** based on the size of the guide wire **1060**, catheter or any other type of elongate member that would be loaded into the elongate member manipulator **1600**. A lookup table of rotations based on type of guide wire or elongate member could be programmed into the system controller and the user could input the information regarding the type of elongate member into the system before use. The look up table could be created using empirical data or calculations based on known mechanical properties of the elongate member. Alternatively, closing and opening of the collet could be based on sensed force during of rotation of the rotation gear **1626**. When the collet solenoid **1632** is actuated to hold the collet teeth **1630** and the collet **1626** is being actuated to close using the rotation gear **1626**, sensing the force imparted on the gear during rotation could be an indicator of when to cease rotation as the collet **1626** closes around the guide wire **1060**. Mechanisms for sensing force will be described in further detail below.

For certain variations of the elongate member manipulator, it can be desirable to provide the capability of measuring the external force applied to the distal end of the elongate member, e.g., a guide wire. Thus, if the distal tip of the guide wire makes contact with tissue, the user could be aware of the force being applied to the tissue. The elongate member manipulator **1600** illustrated in FIGS. **124**A-C can include a variation of force sensing that provides for force sensing during insert/retract and roll actuation of the guide wire **1060**.

FIG. **127**A illustrates the rotation drive **1620** for the elongate member manipulator **1600** and FIG. **127**B illustrates a side cross sectional side view of rotation drive **1620** displaying a load cell **1642** mounted stationary relative to the rotation base **1618** and a fulcrum **1644** which allows the lower portion of the rotation drive bracket **1622** to pivot towards or away from the load cell **1642**. Thus any forces experienced by the guide wire **1060** which is held securely in the collet **1628**, will cause the rotation drive bracket **1622** to transmit forces to the load cell **1642**. With known kinematics and base-lining of initial load cell readings, force applied to the distal tip of the guide wire may be calculated.

FIG. **127**C illustrates a side view of the rotation drive **1620** with a back cross sectional view of the rotation drive **1620**. In this variation, the roll motor **1604** is mounted to a motor bracket **1646** which is supported on a set of bearings **1648** which constrain the bracket **1646** in a fixed vertical and horizontal position yet allow the bracket **1646** to rotate about the roll motor rotational axis as illustrated by the arrows **1652**. The bracket **1646** can include a lever **1654** which can be positioned against an LVDT sensor **1656** that can be fixably mounted to the rotation drive bracket **1622**. Thus a reactive torque imparted on the motor **1604** in the rotational direction would be transmitted to the LVDT **1654** and could be read as resistive force experienced by the guide wire **1060** during a roll actuation. In order to prevent damage to the LVDT **1654**, hard stops **1650** could be mounted to the rotation drive bracket **1622**.

FIG. **112**A illustrates a variation of an apparatus that provides force measurement of a guide wire distal tip during insert. FIG. **112**A shows a bottom perspective view of the elongate member manipulator **1200**. It should be understood that the elongate member manipulator **1200** is shown by way of example, and this force sensing apparatus could be used for any of the elongate member manipulators described herein. The lower slide assembly **1230** is mounted to the manipulator mounting bracket **1058** to which a strain gauge **1080** is also mounted. When force is applied to the distal tip of the guide wire **1060**, the lower slide assembly **1230** mounted to the manipulator mounting bracket **1058** is displaced causing a reading in the strain gauge **1080**. The strain reading can be used to calculate a guide wire distal tip force.

An alternative variation of a force measurement apparatus is illustrated in FIG. **112**B. In this variation, the elongate member manipulator **1500** is shown with a strain gauge load cell **1082** fixably mounted to the manipulator base **1570**. The manipulator base **1570** is mounted to the manipulator mounting bracket **1058** using a pair of linear slides **1084** which allow movement of the manipulator base **1570** and thus the elongate member manipulator **1500** in the insert/retract direction or the direction along the axis of the guide wire (not shown in FIG. **112**B). A force sensing block **1086** is fixably mounted to the manipulator mounting bracket **1058** but is positioned so that it fits between the arms of the load cell **1082**. When an external force is applied to the distal tip of the guide wire (not shown), the elongate member manipulator **1500** is moved back in the retract direction along with the manipulator base **1570** via the linear slides **1084**. The load cell **1082** is also pushed in the retract direction making contact with the force sensing block **1086** resulting in a force reading from the load cell **1082**.

Strain gauges or load cells mounted to the manipulator base **1470**, **1570** or bottom of the elongate member manipulator **1200**, **1300** may be used to sense distal tip force for any of the variations of elongate member manipulators described previously in a manner described above. However, other types of sensors mounted to either the distal tip of the elongate member or on the proximal end of the elongate member on the elongate member manipulator may be used to detect distal tip force including but not limited to strain gauges, piezoelectric sensors, tactile sensors, and quartz force sensors. Alternatively, sensors can be used to detect a change in length of the elongate member which measurement can be used in combination with known mechanical properties to calculate force. Examples of such sensors include but are not limited to a fibers, optical sensors, electromagnetic sensors, inductive sensors, capacitive sensors, vision systems etc.

The elongate member manipulators described herein may be mounted to any type of structure depending on the desired use and any environmental constraints. In one variation, the elongate member manipulator may be mounted to a stationary arm mounted to a bedside rail of a patient bed. In alternative variations, the elongate member manipulator could be mounted to a bedside cart. In the variation shown back in FIG. **83**A, the elongate member manipulator **1200** is mounted directly to the manipulator mounting bracket **1058**, which is fixably mounted to the instrument driver **1016**. The elongate member manipulator **1300** could be mounted in a similar fashion. FIGS. **98**B and **103** show the elongate member manipulator (**1400** and **1500** respectively) each including a manipulator base **1470**, **1570** which is fixably mounted to the manipulator mounting bracket **1058**, which is fixably mounted to the instrument driver **1016**. The various mounting mechanisms for mounting the instrument driver to a bedside rail or cart were described previously.

One example of a mechanism for mounting the manipulator mounting bracket **1058** to the instrument driver **1200** is best shown in FIG. **103**. Though the elongate member manipulator **1500** is shown in this figure, it should be understood that any of the elongate member manipulators described herein can be mounted in the same manner using the same apparatus. In this variation, a vise clamp **1062**, such as one found from CarrLane Tiny Vise™, which provides a clamp as well as a captured hex screw, can be used to fixably attach the manipulator mounting bracket **1058** to a tapped hole **1064** on the instrument driver **1200**. The vise clamp **1062** provides enough clamping force as well as thrust force to securely attach the mounting bracket **1058** to the instrument driver **1200** while preventing the mounting bracket **1058** from lifting away from the instrument driver **1200** due to the weight of the elongate member manipulator **1500**. In an alternative variation an adapted vise clamp **1063** may be altered to chamfer the edges **1065** of the vise clamp as shown in FIGS. **103**AA and **103**AB. The adapted vise clamp **1063** can be coupled with a mating bracket (not shown) so that as the adapted vice clamp **1063** is tightened, it expands within the bracket locking it into place as shown with the arrows **1067**. In one variation, a sterile drape (not shown) may be placed between the adapted vise clamp **1063** and the mating bracket (not shown) allowing a separation between sterile and non-sterile components without puncturing the sterile drape, preventing any breakage of the sterile barrier.

In alternative variations, a plurality of different types of mounting screws, bolts, or any fastener sized properly to obtain the desired clamping force could be used in place of the vice clamp **1062** while the mounting bracket **1058** can be dimensioned at a thickness that could prevent lifting due to elongate member manipulator **1400** weight or due to the weight of any of the various elongate manipulators described herein.

FIGS. **103**A-B illustrate variations of a roll support **1580**, **1582**. Depending on the size and type of elongate member or guide wire being used, it may be difficult to provide enough torque at the proximal end of a guide wire or elongate member to accurately roll the distal section. The roll support tube **1580**,**1582** can provide any number of opposing bends necessary, creating a wave with varying pitch and amplitude between successive bends. In one variation, the roll support may be adjustable such that the number of bends can be altered depending on required torque.

Referring to FIG. **103**A, the elongate member manipulator **1500** is shown with the roll support tube **1580**. The roll support tube **1580** may be configured to receive the guide wire **1060** or various sizes and types of guide wires co-axially, and can be provided proximally adjacent to the elongate member manipulator **1500**. The roll support tube **1580** provides rigid curves which place the guide wire **1060** in several bends. As the guide wire **1060** is actuated in roll, the roll support tube **1580** remains in the curved configuration but rotates about the longitudinal axis of the guide wire **1060**. The bends prevent the wire from rolling within the roll support tube, minimizing or eliminating uncontrolled wind up of the guide wire within the support tube or guide catheter. Thus the roll support tube **1580** assists in providing the torque necessary to gain accurate roll control of the wire through the guide catheter (not shown) or support tube (not shown) provided at the distal end of the elongate member manipulator **1500**. In alternative variations, the roll support tube **1580** could be manufactured from a semi-flexible material which provides rigid support during roll actuation. The roll support tube **1580** can be hand molded to provide the necessary bend configuration.

FIG. **103**B illustrates an alternative variation of a roll support tube **1582** which provides bends of variable pitch and amplitude. Because the roll controllability of the guide wire is dependent on the size and material of the wire itself, different wires may require sharper bends in order to gain accurate controllability while bends that are too sharp for some types of wires may cause damage to the wire. Thus a scissor jack support **1582** can be used to provide the bends necessary to provide torque control in an adjustable manner for various types of wire. The scissor jack support **1582** may provide torqueability support in the same manner as the roll support tube **1582** and provides for an adjustability of curve amplitude and pitch.

Referring back to FIG. **1**, an operator **12** is shown at an operator workstation **22** which provides remote control of a guide catheter **1054**, sheath catheter **1044**, and elongate member manipulator. Details regarding the control of the sheath catheter, guide catheter, and instrument driver are provided in the aforementioned incorporated references. Control of an elongate member manipulator can be approached in a manner similar to the way any remotely controlled robotic master slave system would be controlled according to the references incorporated herein or as is well known in the art. The elongate member manipulator systems of any of the previously described variations will be described herein where the master would be an input device such as the operator workstation **22** and the slave would be any of the elongate member

manipulators (**1100**, **1200**, **1300**, **1400** or **1500**). The elongate member manipulator fundamentally has two degrees of freedom, roll and insert, that could be controlled with a single master with two degrees of freedom, or by two separate master devices that each control one degree of freedom. The following provides various masters that provide input for these degrees of freedom. In other variations, the manipulator can provide one or more degrees of freedom controlled by one or more masters.

Referring back to FIG. **2**, an example of an operator workstation **22** providing for inputs for control of the guide catheter, sheath catheter and elongate member manipulator is illustrated. As previously described the operator workstation **22** includes the master input device **1212** acting as a joystick type controller along with the pendant **8** acting as a keyboard type input device. In one variation, the guide catheter is controlled using the master input device **1212** allowing for steering of the distal tip of the guide catheter as viewed on the display monitors **44** while the sheath catheter and the guide wire are controlled using the pendant **8**. As previously described in detail, the master input device **1212** includes several sensors which detect the position of the master input device **1212** shown in this variation as a joystick. Those sensors send signals to the controller that are interpreted as commands.

FIG. **113** illustrates a variation of the pendant **8** of FIG. **2** which would include controls for the sheath catheter and elongate member manipulator. In order to steer the sheath catheter, the bend, insert and rotate controls **1026** located on the right side of the pendant **8** could be used while the rotate and insert controls **1028** located on the lower left side of the pendant **8** could be used to control the elongate member manipulator. In alternative variations, the distal tip of the guide wire could be controlled using the master input device **6** while the guide and sheath catheters are controlled by the control console **8** or the sheath catheter could be controlled by the master input device **6**. In fact any combination of controls could be implemented using either or both the control console **8** and/or the master input device **6**.

The display and force sensing controls **1030** located on the upper left of the control console **8** could be used to control the views on the monitors and activate and control force sensing capabilities respectively and the trackball controls **1032** could be used to control cursors on the display. As described in detail in the aforementioned incorporated references, the display could show images of patient anatomy in the form of models or fluoroscopic images. Cartoon images of the guide, sheath, and guide wire within the patient anatomy can be displayed showing commanded positions. Actual images of the guide, sheath, and guide wire can be shown from fluoroscopic data. Additionally the display can also show force feedback readings

In an alternative variation, it could be desirable for the controls to be located closer to the patient bed. Referring to FIG. **114**A, a variation of the patient bed **1020** is shown with a standalone console **1024** mounted to the bedside rail **1021** such that the operator could control the system from beside the bed. FIG. **114**B illustrates a side view of the standalone console **1024** mounted to the bedside rail **1021** where the patient bed **1020** is not shown for clarity. The standalone console **1024** can rest on a mounting tray **1036** that is fixably attached to the bedside rail **1021** via a clamp **1038**. FIG. **115** illustrates one example of standalone console **1024** which eliminates some components from the control console **1008** and retains the controls for the sheath catheter **1026** and the elongate member manipulator **1028**. In alternative variations, the standalone console **1024** could be used in conjunction with the control console **1008** with two operators working together in which case one console could override controls if conflicting commands are sent from each console of another depending on configuration.

Alternatively, several other types of input devices could be used to provide the signals for the one or more degrees of freedom necessary to control the elongate member manipulator. In the case where either the elongate member manipulator is mounted to a setup structure alone or mounted on the instrument driver, but control of only the elongate member manipulator is necessary, other types of input devices may be used.

FIGS. **116**-**116**N illustrate various master input devices that could be used in place of a joystick controller and/or console.

FIG. **116** illustrates an alternative variation of a master input device. As is well known the art, manual control of guide wires typically includes a two handed sequence to propel a guide wire in the insert or retract directions. Typically the guide wire is coupled to an introducer that can be used as a handle for an operator. The operator will advance the guide wire, by using a front hand to support the introducer and the rear hand to grip the guide wire pushing it through the introducer. This only accounts for advancement of the guide wire a short distance so the front hand may release the introducer, grip the guide wire, allowing the rear hand to release the guide wire in order to grip it a short distance further back along the guide wire. The front hand can now release the guide wire to allow the rear hand to advance the wire. This is repeated until the guide wire is advanced to the desired position typically advancing the wire 1" to 2" at a time. In many cases, the total insert distance can be as far as 2 meters. The wire can be rotated manually using one or both hands to rotate the wire while inserting it.

The master input device shown in FIG. **116** stimulates the motion physicians are accustomed to during manual procedures while eliminating the need for multiple two handed iterations necessary for manual insert. The master input device **1660** can include an insert motor **1662**, a roll motor **1664**, a flexible member **1666**, a handle (not shown), a linear slide **1668**, actuation cables **1670**, pulleys **1672**, and/or a support **1674**. The handle (not shown) is coupled to the flexible member **1666**, which in turn is coupled to the roll motor **1604**, which is fixably mounted to the support **1674**, mounted to the linear slide **1668**. Using the pulleys **1672** and actuation cables **1670** the linear slide **1668** is coupled to the insert motor **1602**. A variety of motors may be utilized, e.g., the motors can be 13 mm DC brush servo motors and the handle can include a grasper button (not shown). The support **1674** can be made from a lightweight material, such as a lightweight plastic and the linear slide **1668** can also be lightweight and low friction.

During operation, the user depresses the grasper button and rotates the handle (not shown). The roll motor **1604** which is equipped with an encoder reads the rotation of the handle and transmits this data to the controller which will control the roll of the elongate member manipulator. In order to control insert, the user depresses the grasper button, moves the handle forwards or backwards along the linear slide **1668**, while the insert motor **1602** encoder reads the rotation of the motor **1602** and thus the linear movement of the handle. This data is again transmitted to the controller. When the user has reached the physical limit of the linear slide **1668**, the grasper button is released and the user may slide the handle to a nominal linear position without sending a signal to the controller indicating desired propelling actuation of the elongate member manipulator.

FIG. **117**A illustrates a master input device based on a slider that can be moved on a fixed rod. When the engage button is pressed the translation and rotation of the slider are measured by sensors and used to command the insert and rotation of the guide wire. When the engage button is released, the slider can be moved freely or alternatively can be spring loaded to return to a fixed position. The slider can be mounted to a handle as shown in FIG. **117**AA.

FIG. **117**B illustrates a paddle switch that could be mounted to the instrument driver **1016** which could control insert, or retract, and/or roll of the guide wire. The paddle switch can be provided with recessed contact switches as shown in FIG. **117**BB that may be pressed to enable the paddle switch. Alternatively the paddle switch can be pinched from both sides as shown in FIG. **117**BBB to activate it. FIG. **117**C illustrates scroll-wheels that can be incorporated into the handle of a master input device. Each scroll-wheel could be used to control a different degree of freedom on the elongate member manipulator. Alternatively FIG. **117**CC shows buttons incorporated on the master input device handle that could control different degrees of freedom on the elongate member manipulator measuring force applied to each button to determine control of the manipulator. FIG. **117**D shows a wheel with a circular cross-sectioned rim. By hiding most of the wheel inside of a housing or below the table surface, the user is presented with a rail that can be moved in a quasi-linear fashion by rolling the wheel. This gives an infinite range of travel device that could be used to control insert of the guide wire. The wheel could be tilted to either side to control roll of the guide wire.

FIG. **117**DD shows another variation where the rail itself is constructed out a series of rollers so that it can be spun to control the roll of the guide wire. FIG. **117**E shows a control plate mounted to a 2-DOF (pitch-roll) rotation platform. This control plate could be manipulated by the physician with either their hand or foot providing pitch motion to control insert or retraction and rolling motion to control guide wire roll. FIGS. **117**F and **117**FF show linear sliders (with an optional engage button) that can be used to control one DOF of the elongate member manipulator. FIG. **117**G shows a touchpad device that could be used to control the guide wire manipulator. Moving the user's finger forwards/backwards would control insertion of the guide wire and moving the user's finger side-to-side would control roll of the guide wire manipulator. Alternatively a trackball could be used in a similar fashion (not shown). FIG. **117**H shows a "clothes-line" type configuration of a wire or cable looped around several pulleys. The user could directly insert, retract and/or roll this wire by hand or through the use of an optional wire torque device to allow for easier gripping of the wire. FIG. **117**I shows a wide variety of buttons that could be used alone or in combination to control the guide wire manipulation device. Various methods of use of such buttons will be described in detail later. FIG. **117**J shows a wrist-mounted master input device. FIG. **117**K shows a hand-held inertial master input device. FIG. **117**L shows a master input device that is manipulated by inserting, retracting and/or rolling the operator's finger. FIG. **117**M shows a haptic feedback master. The user manipulates the master by inserting, retracting and/or rolling it. The master is mounted to a compartment that contains sensors and motors. The master could be free to slide, spring loaded, or fixed. The active master may sense input and provide feedback to the user via motors under servo control.

The input devices may measure a signal from the operator and map this signal into a command to the slave such as the elongate member manipulator. Input devices on the master side may measure various different types of signals including but not limited to force, position, velocity, acceleration, or discrete events such as buttons presses. These measured signals could be converted into commands in the form of force, position, velocity, acceleration, or a higher level task. A few combinations of various input signals to commands will be discussed further using the elongate member manipulator as the slave however it should be understood that these variations will be presented by way of example and not limitation. Any combination of the aforementioned signals and commands could be implemented including types of comparable signals and commands that are not explicitly mentioned but are well known in the art. Additionally, any slave mechanism could be commanded including but not limited to the mechanisms actuating the guide catheter, sheath catheter, and instrument driver.

FIG. **118***a-d* illustrates flow diagrams of the various master-slave control mapping options. FIG. **118***a* illustrates one variation where a position signal is measured from the input master device and a position command is sent to the slave. Motions of the master are translated into motion commands and sent to the slave in a one to one motion in one variation while in an alternative variation the motion command could be subject to a scaling factor or more complex mapping function in a manner described in detail in the aforementioned incorporated references. In some instances the elongate member manipulator has a very large range of motion which may require either the input device to have a comparably large workspace or the input device to have clutching capability allowing it to clutch to different portions of the of the slave workspace. In an alternative variation shown in FIGS. **118***b* and **118***d*, a position signal is measured from the input master device and a velocity command is sent to the slave. This typically involves a master device that is spring-loaded to return to its zero position such that when the user releases, the master returns to zero and the slave stops moving. This approach has the advantage of using a master with a relatively small range of motion to control a very large (up to infinite) range of motion on the slave. In FIG. **118***b* the slave is controlled using velocity commands while in FIG. **118***d* the slave is controlled using position commands. FIG. **118***d* further illustrates a variation where position sensors on the guide wire manipulator itself are used for closed loop iterative control of the guide wire manipulator in order to more accurately position the guide wire manipulator. In yet another variation shown in FIG. **118***c*, a force signal is measured from the input master device and a velocity command is sent to the slave such that a higher force measurement will result in an increased velocity of the slave. Using a device such as the buttons on the MID handle as illustrated in FIG. **117**CC for example, the harder the operator pushes on the button, the faster the elongate member manipulator inserts/rolls. When the operator is not exerting any force, the slave remains still. This configuration allows for a master with a small (near zero) range of motion to control a very large (up to infinite) range of motion on the slave. In further variations, multiple types of input signals can be combined so that arbitrarily complex dynamics between the master and slave can be introduced.

Another configuration may use discrete events such as but not limited to a button press or activation of a switch as an input to the master sending a specified task to the slave. Various types of buttons may be used, as illustrated in FIG. **117**J. In this configuration, a button press of one or several different buttons can be used to command the execution of a potentially complex task. In one example for one degree of freedom, holding down of a single first button may cause a motion in a pre-defined direction at a pre-defined speed and release of the button would cease motion. A second button could be used in same manner to cause motion in an opposite direction at the same pre-defined speed. Using the elongate member manipulator as an example, holding down the first button may cause the elongate member to be inserted at a set speed until the user releases the button. Holding down the second button may cause the elongate member to be retracted at the same speed until the button is released. A second pair of buttons could be used for roll in the clockwise and counter-clockwise directions. Alternatively, the same configuration could be used where a first single button push may start motion and a second push may stop motion or one button could start motion and a second button could stop motion. In another variation, a button push could cause the elongate member manipulator to move in a pre-determined direction, by a pre-determined amount, at a pre-determined speed. The pre-determined amount could be a set distance or a distance based on a relative position of the elongate member, for example, distance from the elongate member to tissue or distance to the end of a guide catheter if the elongate member was traveling co-axially down the lumen of said guide catheter. Alternatively, the speed could be based on the duration of time a button is pushed such that as the button is held longer, the speed gradually increases or after being pushed for a fixed duration of time, the speed increases from one predetermined amount to another. Alternatively, the movement could be based on a pre-determined force, for example the elongate member may insert until it makes contact with an object and a pre-set threshold of distal tip force is reached.

Multiple combinations of buttons, switches, and other types of on/off input devices could be used with multiple combinations of elongate member movement. It should be understood that the aforementioned combinations are by way of example and not limitation and any combination of inputs to motion including equivalents well known in the art may be used.

In the variation shown in FIGS. **1-2** which includes the operator workstation **22**, the controller **55**, and the instrument driver **16**, the operator workstation includes the input controls in the form of a joystick type master input device **1212** and pendant **8**. This variation may be used in a configuration shown in FIG. **119** which displays the sheath catheter assembly **1040**, the guide catheter assembly **1050**, and the elongate member manipulator **1300** mounted to the instrument driver **1016** with an elongate member in the form of a guide wire **1060** loaded in the elongate member manipulator **1300**. The guide wire **1060** is sized to be inserted co-axially into the lumen of the guide catheter **1054**, which in turn is sized to be inserted co-axially into the lumen of the sheath catheter **1044**.

As previously described, the two degrees by which an elongate member, such as a guide wire **1060** may be manipulated using the elongate member manipulator **1300** are insertion/retraction and roll. Due to the remote nature of a catheterization treatment, the elongate member manipulator **1300** will be located a large distance from the tip of the guide catheter **1054**. The insert function assumes the guide wire has high axial stiffness relative to frictional forces between the guide wire and the inner wall of the guide catheter **1054** as well as forces due to contact with tissue. Thus moving the wire a certain distance proximally should correspond directly to motion distal to the catheter tip. FIG. **120** illustrates a control scheme for control of the elongate member manipulator **1300**. The control scheme is a more generalized version of the previously described control schemes shown in FIGS. **118**A-D. In FIG. **120**, the elongate member manipulator inserts and rolls a guide wire according to commands from a master input device. In the currently described variation, the master input device is the joystick and control console. The controller translates the desired actions into voltages and currents which are applied to the guide wire manipulator motor.

As described in detail in the aforementioned incorporated references, both the sheath catheter assembly **1040** and guide catheter assembly **1050** may be mounted on separate carriages that are motor actuated to provide a propelling motion in the insert and retract directions of the guide catheter **1054** and sheath catheter **1044**. In one variation, the elongate member manipulator **1300** is fixably mounted to the same carriage as the guide catheter assembly **1050**. By mounting the elongate member manipulator in this fashion, buckling of the guide wire can be minimized by locating the elongate member manipulator **1300** as close to the proximal end of the guide catheter **1054** as possible and/or maintaining a constant gap between the elongate member manipulator **1300** and guide catheter **1054** proximal end. The constant gap also avoids an inadvertent collision between the elongate member manipulator **1300** and guide catheter assembly **1050**. FIGS. **121**A-B illustrate a block diagram showing a variation where an elongate member manipulator **1300** is coupled to the guide catheter assembly **1050** and the sheath catheter assembly **1040**. The sheath catheter assembly **1040** may be independently actuated in the insert and retract direction from the guide catheter assembly **1050** and the elongate member manipulator **1300**. The elongate member manipulator **1300** and guide catheter assembly may be coupled to the same carriage and thus are inserted or retracted on that carriage simultaneously.

An example of a controls scheme will be described herein for this configuration of a guide wire, guide catheter, and sheath catheter. A guide wire is a thin flexible elongated rod. In one example, the guide wire is sized at roughly half a millimeter in diameter and about a meter long used during non-invasive vascular catheterization procedures, generally for medical treatment. It typically has an extremely flexible distal tip which prevents interaction trauma by deflecting against tissue rather than scraping or piercing tissue when inserted through a patient's vasculature. One possible mode of operation for use of a guide wire includes positioning the guide wire, holding it in a statically fixed position, and then sliding a catheter over the guide wire. When the guide wire is used in conjunction with the robotically steerable guide catheter **1054** and sheath catheter **1044** as in this variation, it is convenient for the operator to have the guide wire be controllable by the robotic system to allow for coordinated motion of the elongate member manipulator **1300** with the guide catheter **1054** and sheath catheter **1044**. FIG. **122** shows a controller flow diagram for the construction of a movable carriage and a coupled elongate member manipulator as shown in FIG. **121**B. The desired action from the master device is coordinated with the actions of other instrument driver **1016** axes to create a joint command for the insert/retract and roll motors. Finally, these commands are applied to the elongate member manipulator motors with a servo controller to achieve the desired position.

Because the guide catheter assembly **1050** is coupled to the elongate member manipulator **1300**, as the guide catheter is inserted, the guide wire is inserted an identical distance. In order to maintain a static position of the guide wire **1060** while sliding the guide catheter **1054** over the guide wire **1060**, the guide wire may be retracted an equal distance using the guide wire manipulator actuation previously described and shown in FIG. **120**. FIG. **121**A shows the insert distances traveled as, x_S, x_G, and x_{wd}. Where:

x_S=insert distance for sheath catheter

x_G=insert distance for guide catheter

x_{wd}=insert distance for guide wire

In order for the position of the guide wire **1060** to remain constant such that the guide wire **1060** is static, $\Delta x_{wd}=0$ and the commanded guide wire position (x_{wp}) can be represented as:

$$x_{wp}=x_{wd}-x_G \tag{1}$$

The movement of the sheath catheter is independent of the guide carriage so is not included in this calculation.

In another variation shown in FIG. **121**B, the elongate member manipulator **1300** and guide catheter assembly **1050** can be mounted to the same carriage as the sheath catheter assembly **1040**. Thus as the sheath catheter **1044** is inserted, the guide catheter **1054**, and guide wire **1060** are inserted the same amount. Additionally, if the guide carriage is independently inserted, the guide catheter **1054** and guide wire **1060** are independently inserted a separate amount. Thus in order for the position of the guide wire **1060** to be static, $\Delta x_{wd}=0$ and the commanded guide wire position (x_{wp}) can be represented as:

$$x_{wp}=x_{wd}-x_G-x_S \tag{2}$$

In one variation, the elongate member manipulator may not retract the guide wire behind the distal tip of the guide catheter such that the guide wire will be immediately available for guiding when desired by the operator. If the guide wire is retracted within the catheter tip, it will need to recover this distance before being available to the physician. This requires the actual guide wire insert position, and guide catheter insert position to be known relative to one another and controlled precisely. Various sensors have been previously described to measure insert of both the guide catheter and the guide wire.

Static friction between the guide wire and the guide catheter can impede distal rotational motion of the guide wire when the proximal end is rolled. Because of the moderate torsional stiffness of guide wires, there can be multiple revolutions of angular difference between the distal and proximal ends of the wire just due to frictional forces. Once the static friction releases, the wire may rotate rapidly until friction stops the motion again creating an undesirable whipping motion. One method of overcoming the static portion of friction is to dither the guide wire insertion while rolling by using the propelling actuation provided by the elongate member manipulator to repeatedly insert and retract the guide wire **1060** a small distance. The axial stiffness will translate motion through the length of the wire and proximal rotation should translate more directly to distal rotation. The dithering motion could be configured to avoid inserting the wire past the point commanded by the operator during the insert dithering.

Manually operated guide wires include an inherent feedback to the operator as resistance to insert and roll felt by the operator's hands. Thus it could be desirable to provide feedback to the operator during robotic control. Feedback could include but not be limited to visual, audible and haptic feedback. Live fluoroscopic images showing the location of the guide wire and catheters relative to patient anatomy could be provided on the display as well as a virtual guide wire image. By monitoring the position of the guide wire in relation to the position of the catheter, i.e. registering the guide wire to the catheter frame, the guide wire position may be displayed. One method of determining relative positions would be to display a virtual wire extended beyond the catheter tip, to scale with the virtual diameters. A numerical distance could replace or accompany such a display. Also, the virtual wire could be striped or otherwise patterned to indicate movement as displayed in FIG. **123**. Another method of registration could include the use of position sensors including but not limited to

EM or fiber sensors as described in detail in the aforementioned incorporated references.

As previously described, insert force can be measured by the elongate member manipulator. Measured force may be simply displayed for the operator to see how much force the manipulator is applying to move the wire. Further, if the wire inputs are provided with a haptic device, this force could be conveyed to the operator in a way such as with a direct force resistance in the haptic device or with a vibration proportional to force. The force may also be used to detect anomalous insertion conditions in order to avoid or compensate. High insertion forces may cause the wire to buckle between the manipulator and catheter. When force exceeds a threshold, the insertion should be halted to avoid buckling or abrading the surfaces of the wire or catheter. Force may also be used to scale motion in an analog manner. For example, slave motion may correspond directly to master commands, so the master motion may be de-scaled to result in less slave motion as described in detail in aforementioned incorporated references.

Additionally, any feedback sensors including but not limited to position, force, and encoders including redundant encoders as well as kinematic data for commanded guide wire position can all be continuously monitored to detect errors if there is a data mismatch.

The above variations of systems and manipulators may be used with guide wires and/or any other elongate member or instrument.

IX. Instinctive Drive

Referring to FIG. **128**A, an overview of an embodiment of a controls system flow is depicted. A master computer **2400** running master input device software, visualization software, instrument localization software, and software to interface with operator control station buttons and/or switches is depicted. In one embodiment, the master input device software is a proprietary module packaged with an off-the-shelf master input device system, such as the Phantom™ from Sensible Devices Corporation, which is configured to communicate with the Phantom™ hardware at a relatively high frequency as prescribed by the manufacturer. Other suitable master input devices are available from suppliers such as Force Dimension of Lausanne, Switzerland. The master input device **12** may also have haptics capability to facilitate feedback to the operator, and the software modules pertinent to such functionality may also be operated on the master computer **2400**. Preferred embodiments of haptics feedback to the operator are discussed in further detail below.

The term “localization” is used in the art in reference to systems for determining and/or monitoring the position of objects, such as medical instruments, in a reference coordinate system. In one embodiment, the instrument localization software is a proprietary module packaged with an off-the-shelf or custom instrument position tracking system, such as those available from Ascension Technology Corporation, Biosense Webster, Inc., Endocardial Solutions, Inc., Boston Scientific (EP Technologies), Medtronic, Inc., and others. Such systems may be capable of providing not only real-time or near real-time positional information, such as X-Y-Z coordinates in a Cartesian coordinate system, but also orientation information relative to a given coordinate axis or system. Some of the commercially-available localization systems use electromagnetic relationships to determine position and/or orientation, while others, such as some of those available from Endocardial Solutions, Inc.—St Jude Medical, utilize potential difference or voltage, as measured between a conductive sensor located on the pertinent instrument and conductive portions of sets of patches placed against the skin, to determine position and/or orientation. Referring to FIGS. **128**B and **128**C, various localization sensing systems may be utilized with the various embodiments of the robotic catheter system disclosed herein. In other embodiments not comprising a localization system to determine the position of various components, kinematic and/or geometric relationships between various components of the system may be utilized to predict the position of one component relative to the position of another. Some embodiments may utilize both localization data and kinematic and/or geometric relationships to determine the positions of various components.

As shown in FIG. **128**B, one preferred localization system comprises an electromagnetic field transmitter **2406** and an electromagnetic field receiver **2402** positioned within the central lumen of a guide catheter **2090** (which may be one or more of the embodiments of the catheter described herein). The transmitter **2406** and receiver **2402** are interfaced with a computer operating software configured to detect the position of the detector relative to the coordinate system of the transmitter **2406** in real or near-real time with high degrees of accuracy. Referring to FIG. **128**C, a similar embodiment is depicted with a receiver **2404** embedded within the guide catheter **2090** construction. Preferred receiver structures may comprise three or more sets of very small coils spatially configured to sense orthogonal aspects of magnetic fields emitted by a transmitter. Such coils may be embedded in a custom configuration within or around the walls of a preferred catheter construct. For example, in one embodiment, two orthogonal coils are embedded within a thin polymeric layer at two slightly flattened surfaces of a catheter **2090** body approximately ninety degrees orthogonal to each other about the longitudinal axis of the catheter **2090** body, and a third coil is embedded in a slight polymer-encapsulated protrusion from the outside of the catheter **2090** body, perpendicular to the other two coils. Due to the very small size of the pertinent coils, the protrusion of the third coil may be minimized. Electronic leads for such coils may also be embedded in the catheter wall, down the length of the catheter body to a position, preferably adjacent an instrument driver, where they may be routed away from the instrument to a computer running localization software and interfaced with a pertinent transmitter.

In another similar embodiment (not shown), one or more conductive rings may be electronically connected to a potential-difference-based localization/orientation system, along with multiple sets, preferably three sets, of conductive skin patches, to provide localization and/or orientation data utilizing a system such as those available from Endocardial Solutions—St. Jude Medical. The one or more conductive rings may be integrated into the walls of the instrument at various longitudinal locations along the instrument, or set of instruments. For example, a guide instrument may have several conductive rings longitudinally displaced from each other toward the distal end of the guide instrument, while a coaxially-coupled sheath instrument may similarly have one or more conductive rings longitudinally displaced from each other toward the distal end of the sheath instrument—to provide precise data regarding the location and/or orientation of the distal ends of each of such instruments.

Referring back to FIG. **128**A, in one embodiment, visualization software runs on the master computer **2400** to facilitate real-time driving and navigation of one or more steerable instruments. In one embodiment, visualization software provides an operator at an operator control station, such as that depicted in FIG. **1**, with a digitized “dashboard” or “windshield” display to enhance instinctive drivability of the pertinent instrumentation within the pertinent tissue structures.

Referring to FIG. **128**D, a simple illustration is useful to explain one embodiment of a preferred relationship between visualization and navigation with a master input device **12**. In the depicted embodiment, two display views **2410**, **2412** are shown. One preferably represents a primary **2410** navigation view, and one may represent a secondary **2412** navigation view. To facilitate instinctive operation of the system, it is preferable to have the master input device coordinate system at least approximately synchronized with the coordinate system of at least one of the two views. Further, it is preferable to provide the operator with one or more secondary views which may be helpful in navigating through challenging tissue structure pathways and geometries.

Using the operation of an automobile as an example, if the master input device is a steering wheel and the operator desires to drive a car in a forward direction using one or more views, his first priority is likely to have a view straight out the windshield, as opposed to a view out the back window, out one of the side windows, or from a car in front of the car that he is operating. The operator might prefer to have the forward windshield view as his primary display view, such that a right turn on the steering wheel takes him right as he observes his primary display, a left turn on the steering wheel takes him left, and so forth. If the operator of the automobile is trying to park the car adjacent another car parked directly in front of him, it might be preferable to also have a view from a camera positioned, for example, upon the sidewalk aimed perpendicularly through the space between the two cars (one driven by the operator and one parked in front of the driven car), so the operator can see the gap closing between his car and the car in front of him as he parks. While the driver might not prefer to have to completely operate his vehicle with the sidewalk perpendicular camera view as his sole visualization for navigation purposes, this view is helpful as a secondary view.

Referring still to FIG. **128**D, if an operator is attempting to navigate a steerable catheter in order to, for example, contact a particular tissue location with the catheter's distal tip, a useful primary navigation view **2410** may comprise a three dimensional digital model of the pertinent tissue structures **2414** through which the operator is navigating the catheter with the master input device **12**, along with a representation of the catheter distal tip location **2416** as viewed along the longitudinal axis of the catheter near the distal tip. This embodiment illustrates a representation of a targeted tissue structure location **2418**, which may be desired in addition to the tissue digital model **2414** information. A useful secondary view **2412**, displayed upon a different monitor, in a different window upon the same monitor, or within the same user interface window, for example, comprises an orthogonal view depicting the catheter tip representation **2416**, and also perhaps a catheter body representation **2420**, to facilitate the operator's driving of the catheter tip toward the desired targeted tissue location **2418**.

In one embodiment, subsequent to development and display of a digital model of pertinent tissue structures, an operator may select one primary and at least one secondary view to facilitate navigation of the instrumentation. By selecting which view is a primary view, the user can automatically toggle a master input device **12** coordinate system to synchronize with the selected primary view. In an embodiment with the leftmost depicted view **2410** selected as the primary view, to navigate toward the targeted tissue site **2418**, the operator should manipulate the master input device **12** forward, to the right, and down. The right view will provide valued navigation information, but will not be as instinctive from a "driving" perspective.

To illustrate: if the operator wishes to insert the catheter tip toward the targeted tissue site **2418** watching only the rightmost view **2412** without the master input device **12** coordinate system synchronized with such view, the operator would have to remember that pushing straight ahead on the master input device will make the distal tip representation **2416** move to the right on the rightmost display **2412**. Should the operator decide to toggle the system to use the rightmost view **2412** as the primary navigation view, the coordinate system of the master input device **12** is then synchronized with that of the rightmost view **2412**, enabling the operator to move the catheter tip **2416** closer to the desired targeted tissue location **2418** by manipulating the master input device **12** down and to the right.

Instinctive drive techniques have been described in U.S. patent application Ser. No. 11/176,598, filed on Jul. 6, 2005, the entire disclosure of which is expressly incorporated by reference herein for all purposes.

The synchronization of coordinate systems described herein may be conducted using fairly conventional mathematic relationships. For example, in one embodiment, the orientation of the distal tip of the catheter may be measured using a 6-axis position sensor system such as those available from Ascension Technology Corporation, Biosense Webster, Inc., Endocardial Solutions, Inc., Boston Scientific (EP Technologies), and others. A 3-axis coordinate frame, C, for locating the distal tip of the catheter, is constructed from this orientation information. The orientation information is used to construct the homogeneous transformation matrix, T_{C0}^{G0}, which transforms a vector in the Catheter coordinate frame "C" to the fixed Global coordinate frame "G" in which the sensor measurements are done (the subscript C_0 and superscript G_0 are used to represent the O'th, or initial, step). As a registration step, the computer graphics view of the catheter is rotated until the master input and the computer graphics view of the catheter distal tip motion are coordinated and aligned with the camera view of the graphics scene. The 3-axis coordinate frame transformation matrix T_{Gref}^{G0} for the camera position of this initial view is stored (subscripts G_{ref} and superscript C_{ref} stand for the global and camera "reference" views). The corresponding catheter "reference view" matrix for the catheter coordinates is obtained as:

$$T_{Cref}^{C0}=T_{G0}^{C0}T_{Gref}^{G0}T_{Cref}^{Gref}=(T_{C0G0})-T_{Gref}^{G0}T_{C1}^{Gi}$$

Also note that the catheter's coordinate frame is fixed in the global reference frame G, thus the transformation matrix between the global frame and the catheter frame is the same in all views, i.e., $T_{C0}^{G0}=T_{Cref}^{Gref}=T_{Ci}^{Gi}$ for any arbitrary view i. The coordination between primary view and master input device coordinate systems is achieved by transforming the master input as follows: Given any arbitrary computer graphics view of the representation, e.g. the i'th view, the 3-axis coordinate frame transformation matrix T_{Gi}^{G0} of the camera view of the computer graphics scene is obtained from the computer graphics software. The corresponding catheter transformation matrix is computed in a similar manner as above:

$$T_{Ci}^{C0}=T_{G0}^{C0}T_{Gi}^{G0}T_{Ci}^{Gi}=(T_{Co}^{G0})^{-1}T_{Gi}^{G0}T_{Ci}^{Gi}$$

The transformation that needs to be applied to the master input which achieves the view coordination is the one that transforms from the reference view that was registered above, to the current ith view, i.e., T_{Cref}^{Ci}. Using the previously computed quantities above, this transform is computed as:

$$T_{Cref}^{Ci}=T_{C0}^{Ci}T_{Cref}^{C0}$$

The master input is transformed into the commanded catheter input by application of the transformation T_{Cref}^{Ci}. Given a command input

$$r_{master} = \begin{bmatrix} x_{master} \\ y_{master} \\ z_{master} \end{bmatrix},$$

one may calculate:

$$r_{catheter} = \begin{bmatrix} x_{catheter} \\ y_{catheter} \\ z_{catheter} \end{bmatrix} = T_{Cref}^{Ci} \begin{bmatrix} x_{master} \\ y_{master} \\ z_{master} \end{bmatrix}.$$

Under such relationships, coordinate systems of the primary view and master input device may be aligned for instinctive operation.

In one or more of the embodiments, the user interface of the robotic system may be configured to allow a user to register (or align) a real image of a catheter (e.g., a fluoroscopic image) with an image of a computer model of the catheter. This results in the real image catheter being in a same orientation as that of the model image, thereby allowing a user to instinctively drive the catheter (e.g., so that a command to move the catheter model to the right will result in the catheter moving to the right in the reference frame of the real image). The model image may be generated using different techniques in different embodiments. In some embodiments, the model image may be generated by a processor using kinematic information (e.g., stress, strain, curvature, amounts of tensions in respective pull wires inside the catheter, etc.) regarding the catheter. In other embodiments, the model image may be generated using a light signal transmitted through a fiber optic that extends along a length of the catheter. Techniques for determining a geometric configuration of an elongated member using light transmitted through a fiber optic have been describe in U.S. patent application Ser. No. 11/690,116, filed on Mar. 22, 2007, the entire disclosure of which is expressly incorporated by reference herein. In further embodiments, the model image of the catheter may be generated (e.g., by a processor) based at least in part on localization data obtained from electromagnetic sensors. Electromagnetic sensors for obtaining localization data for a medical device are well known in the art, and therefore, will not be described in detail herein.

The act of registration (or alignment) between a real image of the device and a model image may be carried out in different manners in different embodiments. For example, in some embodiments, an alignment process may be performed, wherein the user adjusts one or a few inputs to line up a graphic on screen with a fluoro image of the actual catheter. In one such embodiment, the user can adjust one slider on a touchscreen (or a control at a station) to rotate a virtual representation of the catheter within the plane of the fluoro image to align its heading direction at a prescribed location (e.g., location of a control ring in the leader) to that of the real catheter in the fluoro image, and a second slider (or a second control at the station) to rotate the virtual catheter in or out of plane to align its tilt angle to that of the real catheter. In order to align the roll angle, the user may put a slight bend on the catheter (e.g., so that a length of the catheter may appear as a straight line when looking from a proximal or distal end) and rotate it until the bend is aligned with a bend of an actual catheter. For example, the virtual representation of the catheter (in a bent configuration) may be moved using a control (e.g., slider in a touch screen) to align its roll with a roll of the actual catheter that also has a bent configuration. In further embodiments, instead of rotating the catheter, in order to avoid unnecessary catheter movements inside the body, the user may rotate the fluoro C-arm until the catheter bend is in the imaging plane, pointing either to the left or right in that plane. Variations on this process include using other user interfaces or input devices, such as using the trackball on the pendant instead of touchscreen sliders to align the heading and/or tilt angles of the catheter. In further embodiments, the alignment process described above may not be needed. For example, in some cases, if localization information for the catheter is available, then the alignment process may not be performed (unless the localization is imperfect and needs to be adjusted).

Referring back to embodiment of FIG. **128**A, the master computer **2400** also comprises software and hardware interfaces to operator control station buttons, switches, and other input devices which may be utilized, for example, to "freeze" the system by functionally disengaging the master input device as a controls input, or provide toggling between various scaling ratios desired by the operator for manipulated inputs at the master input device **12**. The master computer **2400** has two separate functional connections with the control and instrument driver computer **2422**: one **2426** for passing controls and visualization related commands, such as desired XYZ (in the catheter coordinate system) commands, and one **2428** for passing safety signal commands. Similarly, the control and instrument driver computer **2422** has two separate functional connections with the instrument and instrument driver hardware **2424**: one **2430** for passing control and visualization related commands such as required-torque-related voltages to the amplifiers to drive the motors and encoders, and one **2432** for passing safety signal commands.

In some cases, during use of the robotic system, it may or may not be possible to place the catheter at a desired position, depending on how the catheter is driven. This may be illustrated in the example shown in FIGS. **128**E and **128**F. The catheter tip is shown in a same Cartesian position relative to a reference frame (which may be a distal tip of the sheath, or any location along a length of the catheter or the sheath) in both FIGS. **128**E and **128**F, while in very different joint configurations. If the catheter were in the configuration shown in FIG. **128**E, and the user wants to reach a position incrementally to the left of the catheter tip, but the catheter is already at its maximum articulation, then the desired position of the catheter tip could not be achieved by incrementally moving the tip of the catheter to the left. However, because the desired position is still in the overall workspace, it could be achieved by decreasing the articulation of the catheter, and the insertion, in order to achieve the configuration shown in FIG. **128**F. In one approach, an extra constraint is added, such as by keeping a constant catheter insertion. In this approach, the user is haptically constrained to the surface of a "dome", as shown in FIG. **128**G, and may orient the catheter but not insert or deinsert it. In this implementation, a proxy position is computed using the haptic implicit-surface (e.g., a cardiod-shaped implicit surface intersected with a plane) proxy algorithm, and a force is returned based on a vector between the device position and the proxy position regardless of whether the device position is inside or outside of the implicit surface. In some embodiments, an artificial limit (e.g., a prescribed velocity limit) for the commanded catheter's articulation motion may be provided to prevent the catheter from moving faster than the robot can command/control it. The difference in position between the proxy and the catheter may then be use to provide force feedback that the user is trying to move the catheter too quickly.

In some embodiments, a two-handed driving technique may be provided, in which the user may insert or deinsert the catheter using a first control (e.g., a pendant button), and orient (e.g., steer) it using a second control (e.g., IMC). The two controls may be configured to allow the user to operate them simultaneously, or one after the other. In one implementation, the user interface is configured to allow the user to control both the pendant-based insertion and the IMC-based orientation simultaneously. In another embodiment, two functional modes for IMC driving may be provided. In one mode, the user orients the catheter as previously described. In the other mode, the user may insert or deinsert the catheter by pushing against the haptic constraint(s). In some cases, the IMC is haptically constrained to a line when in this operation mode because the user may "slip" along the convex top of the dome when trying to push inward to de-insert the catheter.

In other embodiments, a haptic "divot" may be placed in the workspace when de-inserting. Various techniques may be used to allow switching between the different modes. For example, in some embodiments, when clutching the IMC, the user may start out in the orientation mode, but when the force applied against the workspace exceeds a certain threshold, the user may be switched into the insert-deinsert mode. In other embodiments, the mode may be controlled by a secondary IMC button or a foot pedal or a pendant button.

In some embodiments, as the user is driving the catheter using the robotic system, the user interface displays an image of the catheter (which may be a real image, or a computer generated model), and the haptic dome of FIG. **27** that follows the distal end of the catheter. The dome represents a constraint for the distal end of the catheter so that at least a part (e.g., the distal tip) of the distal end of the catheter is required to be on an outline of the dome regardless of how the catheter is driven. For example, in one implementation, the user interface provides a first control for allowing the user to advance or retract the catheter, and a second control for allowing the user to steer the catheter. In such cases, if the user attempts to advance or retract the catheter, the tip of the catheter will be constrained to follow the outline of the dome. As a result, the tip of the catheter may "slide" along the outline of the dome in response to the command to advance or retract the catheter. Similarly, if the user attempts to steer the tip of the catheter, the tip of the catheter will also be constrained to follow the outline of the dome, thereby causing the tip of the catheter to "slide" along the outline of the dome in response to the command to steer the catheter. In some embodiments, advancement or retraction of the catheter will change the size of the doom as it is displayed in the screen, while a steering of the catheter will not change the size of the doom. In some embodiments, the dome may have a cardiod shape. In other embodiments, the dome may have other shapes. In some cases, the system is configured to also provide force feedback at the user interface for the user based on the haptic dome. For example, if the processor determines that a command for positioning (advancement, retraction, and/or steering) of the catheter may result in the distal tip of the catheter being away from the outline of the dome, then the user interface will provide a force feedback to indicate to the user that the tip of the catheter is being "pulled" or "compressed" by the outline of the dome. If the user "feels" a restraining force from the user interface as he/she is commanding the catheter to move, the image of the haptic dome will allow the user to see why that may be the case.

In some of the embodiments described herein, the system may also provide speed control for positioning the catheter so that the tip of the catheter cannot be positioned (e.g., advanced, retracted, and/or steered) too fast. In one implementation, a speed limit may be entered into the system. In such cases, if the user attempts to position the catheter in a way that exceeds the speed limit, the processor may control the positioning of the catheter so that it stays below the speed limit, and may cause the user interface to provide a tactile feedback indicating that the speed of the catheter is being controlled.

In some embodiments, the dome reflects the kinematic articulation workspace of the elongate member. The dome is not limited to any particular shape, and may have a cardioid shape, a spherical shape, a cone shape, or any of other shapes. In some embodiments, the dome shape may be user defined. In other embodiments, the dome shape may be determined by the processor. In one implementation, in order to calculate the shape of the dome, the software starts with a cardioid shape (or another arbitrary shape), then searches around that surface for the true limits of the reach by the elongate member.

X. Sterile Adaptor

As described in detail in application Ser. No. 12/614,349 previously incorporated by reference, during surgical robotic procedures, common practice is to place a sterile drape over a robotic assembly such as the previously described instrument driver, then attach sterilized tools onto the robotic assembly over the drape. In this way, the robotic side of the drape is in a non-sterile environment while the surgical side is in a sterile environment. It is often desirable to remove a tool and replace it with an alternative tool which serves an alternative function, then exchange the tools again such that the original tool is replaced. However, once a tool is initially engaged onto the non-sterile robot, it breaks the sterile field making the tool non-sterile, preventing a user from re-installing it without re-sterilizing it. Thus in practice, a user must either sterilize a tool before re-installing it or must treat the tool as a disposable without the capability of re-installation. Re-sterilization is an impractical solution during a procedure and while a disposable tool can be sterilized and used on a later date, it could be costly to continue using new tools during the procedure. Additionally, liquids such as blood or saline are often spilled onto the drape during tool exchange. While tools are removed from anatomy, they are often contaminated with blood that spills specifically in the area where the tool is coupled to the robotic assembly. It is preferable that liquids do not leak into the robotic assembly which may cause a loss of functionality in the electro-mechanical assemblies within the robot. Thus an interface apparatus that prevents fluid ingress while transferring drive motion across a sterile barrier without breaking the sterile barrier may be desirable.

One variation of a drive interface apparatus is illustrated with reference to FIGS. **129**a-**129**c. FIG. **129**a illustrates a version of the previously described instrument driver **16** which includes a sheath output plate **3006** and guide output plate **3008**. A sheath splayer **3003** and a guide splayer **3005** are each mounted indirectly to the sheath output plate **3006** and guide output plate **3008** respectively. It should be noted that the sheath and guide mounting plates along with the sheath and guide splayers are substantially similar in construction and functionality. By way of example, the sheath splayer and sheath output plate will be later described with the understanding that the same construction and functionality can apply to the guide splayer and guide output plate.

FIG. **129**b shows a zoomed in view of a front portion of the instrument driver **16** better illustrating the sheath splayer **3003**, a drive interface apparatus **3004**, a drape assembly

1900, and the sheath output plate **3006**. FIG. **129***c* illustrates an exploded view of the assembly of FIG. **129***b*. The sheath splayer **3003** is removably coupled to the interface apparatus **3004** which in turn is removably coupled to the sheath output plate **3006**. The drape assembly **1900** is compressed between the drive interface apparatus **3004** and the sheath output plate **3006**. For clarity, only portions of the drape assembly **1900** are shown. The full drape assembly **1900** will be described in detail later

FIGS. **130***a* and **130***b* illustrate a top and bottom view respectively of a variation of the sheath output plate **3006**. FIG. **130***c* illustrates a bottom exploded view of the sheath output plate **3006** which includes a base plate **3010**, sliding latches **3012**, four sliding springs **3014**, and two retaining plates **3016**. FIGS. **131***a-b* illustrates a top and bottom perspective view of the base plate **3010** which includes drive interface alignment holes **3026**, contact pin holes **3028**, cutouts **3018**, latch walls **3020**, and latch pins **3022**. The sliding latches **3012** can fit into the cutout **3018** in the bottom of the base plate **3010** with the two sliding springs **3014** each compressed between a ridge of the sliding latch **3012** and the latch wall **3020** in the cutout **3018**. The retaining plates **3016** can be fixed to the base plate **3010** with screws (not shown in the figures) holding the sliding latches **3012** and sliding springs **3014** in place. By way of example, the base plate **3010** can be made of 6061-T6 aluminum, the latches can be made of 316 stainless steel, and the retaining plates **3016** can be made of high hardness stainless steel.

FIG. **131***c* illustrates a variation of the guide output plate **3008** which can utilize an alternatively shaped guide output base plate **3024** configured to provide a mount for a clamp holding the handle of a working catheter. The main body **3025** of the guide output plate **3008** can remain substantially identical to that of the sheath output plate **3006**. Thus the same type of spring loaded sliding latch mechanisms described for the sheath output plate **3006** can be used for the guide output plate **3008**. For both the guide and sheath output plates **3008**, **3006** the sliding latches can be used to attach and detach the drive interface apparatus **3004** as will be described in detail later.

FIG. **132***a*-**132***b* illustrate top and bottom perspective views of the drive interface apparatus **3004** while FIG. **132***c* illustrates an exploded view. The drive interface apparatus **3004** can include a drive interface base **3030**, drive interface pulley shafts **3048**, drive interface shaft pins **3050**, conductive spring loaded EEPROM pins **3052**, and a splash deflector **3054**.

FIG. **133***a*-**133***b* illustrates top and bottom perspective views of the drive interface base **3030** which includes top static latches **3032**, bottom static latches **3034**, pulley holes **3036**, pin holes **3038**, splayer holes **3040**, and output plate alignment pins **3042**. The top and bottom static latches **3032**, **3034** can be non-adjustable, non-movable protrusions which as will be described in detail later could be used to lock the splayer **3002** to the drive interface apparatus **3004** and the drive interface apparatus **3004** to either the sheath or guide output plates **3006**,**3008**. The splayer holes **3040** and output plate alignment pins **3042** can be used to help with installation of the drive interface apparatus **3004** and the sheath splayer **3003**.

FIGS. **134***a*-**134***b* illustrate top and bottom views of the drive interface base **3030** with the drive interface pulley shafts **3048** and EEPROM pins **3052** installed into the pulley holes **3036** and pin holes **3038** respectively. The bottom portions of drive interface pulley shafts **3038** and EEPROM pins **3052** protrude through the drive interface base **3030** while resting within the drive interface base **3030**. Referring back to FIGS. **4132***a* and **132***c*, the splash deflector **3044** which is illustrated with cutouts that provide clearance for the top static latches **3032**, drive interface pulley shafts **3048**, and EEPROM pins **3052** can be installed onto the drive interface base **3030**. The splash deflector **3044** not only provides for exclusion of debris and liquids but it also constrains the drive interface pulley shafts **3048** from movement in the vertical and horizontal plane while allowing free rotational movement about their respective axes.

FIG. **135***a*-**135***c* illustrates perspective and zoomed in views of the drape assembly **1900**. Among other components that operate with a guide wire manipulator which will be described later, the drape assembly includes a drape body **1901**, a sheath foam pad **1902**, a guide foam pad **1904**, protective tabs **1906**, and an alignment aid **1908**. The sheath foam pad **1902** is similar in construction to the guide foam pad **1904**, each provided with cutouts to mate with guide or sheath output plates **3008**, **3006** as well as the drive interface apparatus **3004**. The sheath and guide foam pads **1902**, **1904** can be constructed from any number of compressible materials including but not limited to polyurethane foam while the protective tabs and alignment aid can be made of High-density polyethylene (HDPE). The drape body **1901** can be constructed of any type of sheer plastic including but not limited to polyethelene.

FIGS. **136***a-b* illustrate different types of splayers that may be used in conjunction with the previously described drive interface apparatus. FIG. **136***a* illustrates a perspective view of a variation of the sheath splayer **3003** while FIG. **136***b* illustrates a perspective view of a variation of the guide splayer **3005**. The sheath splayer **3003** includes a splayer body **3002**, a sheath active valve assembly **3080**, a sheath anti-buckling interface **3074**, and a sheath catheter **3000**. The guide splayer **3005** includes a splayer body **3002**, a guide flush assembly **3082**, a guide anti-buckling interface **3076**, and a guide catheter **3001**. Referring to FIG. **136***c* the sheath splayer **3003** is shown with a sheath cover **3062** exploded from the remaining components of the sheath splayer to illustrate how the sheath active valve **3080**, sheath catheter **3000** and sheath anti-buckling interface **3074** are integrated with the splayer body **3002**. The sheath splayer **3003** has a substantially identical splayer body **3002** to the guide splayer **3005** so integration of the guide flush assembly **3082**, the guide anti-buckling interface **3076**, and the guide catheter **3001** is similar.

Referring to FIG. **137***a-c*, the splayer body **3002** will be described in more detail. FIG. **137***a* illustrates a top perspective view, FIG. **137***b* illustrates a bottom perspective view, and FIG. **137***c* illustrates an exploded view. The splayer body **3002** can include a splayer base **3060**, a splayer cover **3062**, splayer pulley assemblies **3064**, a splayer ID chip **3066**, an ID chip cover **3070**, a splayer presence magnet **3072**, and splayer body screws **1073**.

The splayer cover **3062** shown in FIG. **138** can include a pair of splayer latches **3084** coupled to pair of urethane based compliant members **3086** allowing the latches to be repositioned with applied manual forces. Perspective and exploded views of the splayer pulley assembly **3064** are illustrated in FIGS. **138***a*-**138***b* respectively. The pulley assembly **3064** includes a pulley **3102**, a set of outer races **3104**, a set of ball cages **3110**, a set of ball bearings **3108**, and a set of retainer clips **3106**. The pulley **3102** can be constructed of plastic and provided with an internal spline **3112** profile and with a feature **3114** for coupling with a pull wire crimp ball located at the end of a catheter pull wire or control wire (well known in the art and described in detail in applications previously incorporated by reference). The retainer clips **3106** fit onto the pulley **3102** to hold the crimp balls (not shown) and bearings **3108** in place. The inner races of the ball bearings are integrated into the pulley in order to achieve a low profile package and minimize assembly processes. The pull wire (not shown) is wound around the pulley **3102** and is run down the length of a catheter shaft as previously described. The splayer ID chip **3066** includes a pair of pogo pins **3068**. The magnet can be constructed of various materials including but not limited to a single neodymium magnet. The splayer base **3060** illustrated in FIGS. **139***a-b* can be configured with pulley pockets **3092**, an ID chip pocket **3094**, a magnet pocket **3096**, cover mounting holes **3090**, and latch holes **3091**. The bottom of the splayer base **3060** can also include splayer alignment pins **3088**.

FIGS. **140***a-b* illustrate the splayer base **3060** with the splayer pulley assemblies **3064**, splayer ID chip **3066**, and splayer presence magnet **3072** installed. The splayer pulley assemblies **3064** rest within the pulley pockets **3092** in a manner that allows the each pulley **3102** to rotate about its own axis within the ball bearing **3108**. The splayer presence magnet **3072** rests in the magnet pocket **3096**. The ID chip pocket **3094** is sized to recess the ID chip **3094** allowing for a low overall splayer profile. The ID chip cover **3070** is installed over the splayer ID chip **3066**, protecting the ID chip while allowing the pogo pins **3068** to protrude through. To hold the pulley assemblies **3064** in place, the splayer cover **3062** is mounted to the splayer base **3060** with the splayer body screws **3073** which fit through the cover mounting holes **3090**. The splayer latches **3084** fit through the latch holes **3091**, protruding out of the bottom of the splayer base **3060**. While four pulley assemblies **3064** are illustrated, alternative variations can include any number of pulley assemblies **3064** leaving any number of pulley pockets **3092** empty. The ID chip **3094** is used to transfer device information to the instrument driver (not shown) while the presence magnet **3072** detects when the splayer **3003** is installed on the instrument driver.

Referring to FIG. **141***a* one method of installation of the drape assembly **1900** onto the instrument driver **16** is shown. As shown in FIG. **141***b* the drape assembly **1900** is placed on top of the instrument driver **16** aligning the sheath foam pad **1902** and to the sheath output plate **3006** so that the holes in the foam pad **1902** line up with the holes in the output plate **3006**. The same method can be performed for the guide foam pad **1904** and the guide output plate **3008**.

A first and second drive interface apparatus can now be installed over the drape assembly **1900** onto the sheath output plate **3006** and guide output plate **3008**. The following will illustrate a method of installation for the sheath output plate **3006** but it should be understood that substantially identical methods may be implemented for the guide output plate **3008**. FIGS. **142***a* and **142***b* illustrate the drive interface apparatus **3004** uninstalled and installed respectively onto the instrument driver **16** with the drape assembly **1900** installed onto the sheath output plate **3006**. FIGS. **143***a*-**143***c* illustrate top and bottom views of only the sterile face apparatus **3004** uninstalled on the sheath output plate **3006** and drape assembly **1900**. The drive interface apparatus **3004** can be installed over the sheath foam pad **1902** inserting the drive interface pulley shafts **3048** through the holes in the sterile drape foam pad **1902** and output plate **3006** as shown in FIG. **143**. The foam pad **1902** is compressed between the drive interface apparatus and the output plates **3004**, **3006** creating a seal preventing liquid ingress. The drive interface pulley shafts **3048** couple to the sleeve receptacles **56***b* by engaging the drive interface shaft pins **3050** into notches in the sleeve receptacles **56***b* as shown in FIGS. **144***a-d*. To aid in alignment of the drive interface apparatus **3004** with the sheath output plate **3006**, the output plate alignment pins **3042** fit into the drive interface alignment holes **3026**. As the drive interface apparatus **3004** is pressed down onto the output plate **3006**, the ramped bottom static latches **3034** on the drive interface base **3030** force the spring loaded sliding latches **3012** apart allowing the bottom static latches to insert into the latch holes **3011**. The sliding springs **3014** force the sliding latches apart locking the bottom static latches **3034** to the output plate **3006**. The sliding springs **3014** are sized to compress easily enough to allow a one handed press installation of the drive interface apparatus **3004** while being strong enough to expand locking the static latches in place. To un-install the drive interface apparatus **3004** from the output plate **3006**, the sliding latches **3012** on the output plate **3006** can be pressed towards the center of the output plate **3006**, releasing the bottom static latches **3034** from the output plate **3006**.

Once the drive interface apparatus is installed as described above, the guide or sheath splayer **3005**, **3003** can be installed and easily uninstalled onto the drive interface apparatus **3004** without breaking the sterile barrier created by the sterile drape assembly **1900**. Referring to FIG. **145***a-b*, one method of installation of the sheath splayer **3003** to the drive interface apparatus **3004** is shown. For clarity, the instrument driver and drape assembly are not shown. The sheath splayer **3003** can be installed to the drive interface apparatus **3004** coupling the splayer pulleys **3102** to the drive interface shafts **3048**. The splayer pulleys **3102** are free to rotate within the splayer **3003** before installation onto the drive interface apparatus **3004**. Once engaged with the drive interface pulley shafts **3048**, the splayer pulley assemblies **3064** lock onto the drive interface pulley shafts **3048**. The splayer pulleys **3102** are configured in a similar manner as VHS type with internal splines **3112** that are shaped to ensure consistent self alignment of the pulley **3102** to the interface pulley shaft **3048** and to aid in minimizing insertion and removal force of the splayer **3003** from the drive interface apparatus **3004** as shown in FIGS. **146***a-b* which illustrates top views of the splayer pulleys **3102** and the interface pulley shafts **3048**. For further illustration, FIGS. **147***a-b* provide various perspective views of a single splayer pulley **3102** and interface pulley shaft **3048**.

To aide in alignment of the sheath splayer to the drive interface apparatus, the splayer alignment pins **3088** on the bottom of the splayer **3003** can mate with the splayer holes **3040** on the drive interface apparatus **3004**. To lock the splayer **3003** to drive interface apparatus **3004** force applied to the top of the splayer **3003** will force the splayer latches **3084** to displace until they lock with the top static latches **3032** on the drive interface apparatus. The spring force of the compliant members **3086** in the splayer cover **3062** force the splayer latches **3084** to return to their nominal positions locking the splayer latches **3084** to the top static latches **3032**. In order to remove the splayer **3003** from the system, the splayer latches **3084** are compressed by squeezing either side of the splayer cover **3062**, re-positioning the compliant members **3086** and releasing the splayer latches **3084** from the drive interface top static latches **3032**.

Referring to FIGS. **148***a*-**148***b*, the transfer of motion from the instrument driver **16** to the sheath splayer **3003** actuating bending of the sheath catheter **3000** will be shown. FIG. **148***a-b* illustrates a top and bottom view respectively of the instrument driver **16** with its cover removed. As previously described, various articulation mechanics **3029** including motors, pulleys belts and gears can drive the motorized rotation of sleeve receptacles **56***b* which couple to the drive interface pulley shafts **3048**. As was illustrated in FIGS. **144***a*-**16***d*, the drive interface pulleys shafts **3038** can each be provided with drive interface shaft pins **3040** that allow the shafts **3038** to be coupled to the sleeve receptacles **56***b*. In turn the splayer pulley assemblies **3064** couple to the drive interface pulley shafts **3038**. Thus motorized rotation of the sleeve receptacles ultimately actuates rotation of the splayer pulley assemblies. As previously described, pull wires that run the length of the catheter are controlled by the rotation of the splayer pulley assemblies **3064** to actuate bending at the distal tips of the catheter.

FIGS. **148***a*-**148***b* also illustrate the EEPROM pins **3052** of the drive interface apparatus **3004** which can pass through holes **3028** in the output plate **3006** in order to couple to a circuit mounted (not shown) beneath the output plate **3006**. Once the splayer **3003** is installed, the pogo pins **3068** on the splayer ID chip **3066** make contact with the conductive contacts **3052** shown allowing the ID chip **3066** to connect to the circuit and transmit catheter parameter data to the robotic system. Also a splayer presence magnet **3072** shown in FIG. **9***c* is included on the splayer **3003** that is detected by a switch (not shown) on the instrument driver **16**. The presence magnet **3072** can be sized appropriately for detection by a switch mounted within the instrument driver **16** through the drive interface apparatus **3004**.

Referring back to FIGS. **135***a*-**135***c*, the drape can be provided with protective tabs to prevent accidental removal of the drive interface apparatus during the removal of the splayer. As shown in FIG. **135***b*-**135***c*, protective tabs **1906** can be provided on the drape body **1901** to cover the sliding latches **3012** on the output plate **3006** preventing the user from accidentally compressing the sliding latches **3006** during a procedure when the intention is to release the splayer latches **3084**. The drape assembly **1900** also includes an alignment aid **1908** that may be used to aid in positioning of the instrument driver **16** to a patient entry site. When the instrument driver **16** is positioned near the patient, the alignment aid **1908** can be positioned such that its distal tip makes contact with the patient skin setting the distance between the instrument driver nose and the patient. The alignment aid **1908** can be configured such that its overall length is longer than the length of an anti-buckling mechanism (previously described) in its fully compressed state. Thus the distance between the instrument driver and patient will be sufficient to allow for installation of the anti-buckling device without causing undesired force of the anti-buckling device on the patient tissue. The alignment aid may also include an alignment line which coincides with the centerline of the instrument driver **16**. The alignment line can be used as a visual aid in alignment of the instrument driver to an introducer or guide wire inserted in a patient vessel. Since the introducer or guide wire will tend to naturally align with the vessel, alignment of the instrument driver to the introducer or guide wire will help with better alignment with the patient vessel. The position of the instrument driver **16** can be saved in the system memory and the alignment aid can be removed from the drape for the remainder of the surgical procedure.

Each of the individual variations described and illustrated herein has discrete components and features which may be readily separated from or combined with the features of any of the other variations. Modifications may be made to adapt a particular situation, material, composition of matter, process, process act(s) or step(s) to the objective(s), spirit or scope of the present application. Also, any of the features described herein with reference to a robotic system is not limited to being implemented in a robotic system, and may be implemented in any non-robotic system, such as a device operated manually.

Methods recited herein may be carried out in any order of the recited events which is logically possible, as well as the recited order of events. Furthermore, where a range of values is provided, every intervening value between the upper and lower limit of that range and any other stated or intervening value in that stated range is encompassed. Also, any optional feature of the inventive variations described may be set forth and claimed independently, or in combination with any one or more of the features described herein.

All existing subject matter mentioned herein (e.g., publications, patents, patent applications and hardware) is incorporated by reference herein in its entirety except insofar as the subject matter may conflict with that described herein (in which case what is present herein shall prevail). The referenced items are provided solely for their disclosure prior to the filing date of the present application. Nothing herein is to be construed as an admission that any claimed invention is not entitled to antedate such material by virtue of prior invention.

Reference to a singular item, includes the possibility that there are plural of the same items present. More specifically, as used herein and in the appended claims, the singular forms "a," "an," "said" and "the" include plural referents unless the context clearly dictates otherwise. It is further noted that the claims may be drafted to exclude any optional element. As such, this statement is intended to serve as antecedent basis for use of such exclusive terminology as "solely," "only" and the like in connection with the recitation of claim elements, or use of a "negative" limitation. Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art in the field of this application.

Although particular embodiments have been shown and described, it will be understood that they are not intended to limit the claimed inventions, and it will be obvious to those skilled in the art having the benefit of this disclosure that various changes and modifications may be made. The specification and drawings are, accordingly, to be regarded in an illustrative rather than restrictive sense. The claimed inventions are intended to cover alternatives, modifications, and equivalents.

The invention claimed is:

1. A robotic surgical system, comprising:

a controller including a master input device;

an instrument driver in communication with the controller; and

an elongate member manipulator coupled to the instrument driver, the elongate member manipulator comprising:

a drive belt assembly;

an idler belt assembly, comprising a plurality of spaced idler belts; and

a drive assembly, comprising an insert motor, a roll motor, and a slide assembly,

wherein the drive assembly is responsive to control signals generated, at least in part, by the master input device of the controller,

wherein the insert motor of the drive assembly is configured to actuate the drive belt assembly and the idler belt assembly in opposite rotational directions to generate a corresponding linear motion of the elongate member along a longitudinal axis of the elongate member, and

wherein the roll motor of the drive assembly is configured to move the slide assembly to actuate the drive belt assembly and the idler belt assembly in opposite linear directions to generate a corresponding rotational motion of the elongate member about the longitudinal axis of the elongate member.

2. The robotic surgical system of claim **1**, wherein the drive assembly is configured to actuate the drive belt assembly and the idler belt assembly in rotational and linear directions simultaneously.

3. The robotic surgical system of claim **2**, wherein the drive belt assembly and the idler belt assembly are actuated in the rotational and linear directions at different respective rates.

4. The robotic surgical system of claim **1**, wherein the drive assembly is configured to provide rotational actuation and linear actuation for the drive belt assembly and the idler belt assembly separately, and wherein the drive belt assembly and the idler belt assembly are configured to maintain engagement with the elongate member between the rotational actuation and linear actuation.

5. The robotic surgical system of claim **1**, wherein the elongate member comprises a guide wire.

6. The robotic surgical system of claim **1**, further comprising an elongate member support configured to hold the elongate member and to prevent buckling of the elongate member during rotational or linear motion of the elongate member.

7. The robotic surgical system of claim **6**, wherein the plurality of spaced idler belts of the idler belt assembly are configured to provide clearance for at least a portion of the elongate member support.

8. The robotic surgical system of claim **6**, wherein the drive belt assembly comprises a drive belt weaved around a plurality of reverse idlers to create a multiple segmented belt, the multiple segmented belt configured to provide clearance for a portion of the elongate member support.

9. The robotic surgical system of claim **6**, wherein the elongate member support has one or more protrusions with grooves, wherein the grooves are configured to hold the elongate member to prevent buckling of the elongate member during rotational or linear motion of the elongate member, and the protrusions are positioned between the spaced idler belts.

10. The robotic surgical system of claim **1**, further comprising a roll support configured to position the elongate member so that a bend in the elongate member faces towards a first direction, and to position the elongate member so that the bend faces towards a second direction that is opposite from the first direction.

11. The robotic surgical system of claim **10**, wherein the roll support comprises a scissor jack.

12. The robotic surgical system of claim **1**, further comprising a force sensor to measure force at a distal tip of the elongate member.

13. The robotic surgical system of claim **1**, further comprising one or more slip rollers for gripping the elongate member, wherein the slip rollers are decoupled from the drive belt assembly and the idler belt assembly to detect sliding or slipping of the elongate member between the drive belt assembly and the idler belt assembly.

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